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A STUDY OF PILOT ACCEPTANCE FACTORS IN THE DEVELOPMENT OF ALL-WEATHER LANDING SYSTEMS

by Harold E. Price, Ewart E. Smith, and Walter B. Gartner

Prepared under Contract No. NAS 2-1346 *by*
SERENDIPITY ASSOCIATES
Sherman Oaks, California
for

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FOREWORD

Much of the descriptive material and a number of figures representing analytical data and flight control techniques appearing in this report have been freely abstracted from the reference documents cited in the text and our indebtedness to the originators of this material is hereby acknowledged. It should be noted that this report was produced, in part, in order to document an extensive review and integration of information pertinent to requirements for all-weather landing systems and related technical developments and proposals. The material was compiled in order to support subsequent research activities and the report is in no way concerned with evaluating the technical developments cited herein. It is hoped that no misrepresentation of the problems and techniques covered has occurred and the authors accept full responsibility for any distortion of data which may have occurred in the abstraction from original sources.

CONTENTS

1. INTRODUCTION

1.1 PURPOSE OF THE REPORT AND PROJECT OBJECTIVES

This report presents the results of the first phase of a study of pilot acceptance factors in the development of all-weather landing systems. The study is being pursued under contract NAS2-1346. The broad objective of the research program supported by the material in this report is to identify generalizable principles and criteria for incorporating human user/operator acceptance data into decision making activities directed toward the optimum allocation of functions in man-machine systems. Current research efforts are concerned with pilot acceptance factors in the design and operational employment of automated landing systems for contemporary and near-future commercial air transport operations. Phase 1 of this research effort was directed toward a delineation of all-weather landing system (ALS) functions and a review of flight control function allocation in ALS's which have been proposed and/or are now under development. Subsequent phases of the research program, which are discussed more fully in Section 2, will be concerned with a determination and evaluation of pilot acceptance problems with respect to specific ALS function allocation and design characteristics (Phase 2), the identification of techniques for resolving specific acceptance problems and establishing positive acceptance (Phase 3), and the testing and evaluation of techniques for establishing positive acceptance (Phase 4).

The material presented in this report is based, to a large extent, on an extensive review of the literature pertinent to ALS requirements and design concepts and on information obtained in initial contact interviews with representatives of the major airlines, ALS equipment manufacturers, and airline industry associations, such as the ALPA. It was compiled in order to document selected information pertinent to the all weather landing problem, flight control techniques, and developmental and proposed systems for implementing landing functions. In addition, initial efforts to obtain pilot acceptance data and current plans for the reduction and analysis of these data are discussed.

1.2 SERENDIPITY'S ORIENTATION TOWARD THE ACHIEVEMENT OF RESEARCH PROGRAM OBJECTIVES

One approach to achieving the long-standing objective of highly reliable aircraft landing operations under severely degraded visibility conditions lies in the increased application of automatic flight control techniques. In currently operational systems automatic control is generally regarded as a convenience for relieving pilots of continuous, routine flight control tasks. For critical control tasks, such as flareout and touchdown, manual control is assumed. However, currently operational systems do not meet the safety and reliability requirements for ICAO Category III operations ("zero-zero" ceiling and visibility minima) and it is widely believed that ultimate landing systems will of necessity be capable of fully automatic operation. Systems providing for automatic control of aircraft landing through touchdown and roll-out have already been developed and flight tested. The further development and employment of such systems is expected to be a critical factor in the successful all-weather operation of hypersonic aircraft and in the recovery of space vehicles capable of aerodynamic control. In addition, the rapidly advancing technology in the development of flight control systems is expected to lead to requirements for automated control systems for vehicle recovery and landing even under VFR conditions.

The development of highly reliable automatic landing systems by the best engineering talent available will not solve all the problems associated with their effective employment and will, in fact, create new problems. For many years to come landing systems will be man-machine systems that, at a minimum, will require a man to initiate the machine functions, monitor them, and decide when to disengage and override them. It is here asserted that if all man-machine interfaces are not optimum, system effectiveness cannot be optimum, since it will be under-used and/or used improperly, either covertly or overtly. Man-machine interfaces must be designed to be compatible with the total man, not just his perceptual and motor "subsystems." Traditional human engineering, usually performed after the system has been designed and the breadboard equipment developed by engineers, has been applied as if man were rational and as if it were only necessary to consider such aspects of man as his perceptual and motor capabilities. In actual fact, however, it is equally if not more important to consider man's fears, anxieties, aspirations, etc., when designing man-machine systems. If a system is designed so that it is easy for the man to grasp and manipulate the controls, and if the displays are easy for him to perceive and understand, then, certainly, the system will be more acceptable and utilization will be enhanced. But if the system, even incorporating these features, is believed by the man to be a threat to his physiological or economic survival, or to his social status, he will reject, sabotage, under-use or misuse the system, consciously or unconsciously, and often with justifications on other grounds, such as "No ILS will ever be reliable below 300 feet."

What is needed is the development of techniques for utilizing data on human acceptance attitudes toward the automation of specific functions and/or how they are automated, and this information is needed when function allocation decisions are being made. This will permit the incorporation of acceptance factors as additional criteria in trade-off analyses which already include a consideration of the performance capbilities and reliabilities of man and machine components. It may be found, for example, that a decision to automate a particular function based upon sound engineering considerations would produce a degree of negative acceptance that would clearly offset the anticipated advantages of the engineering solution. These cases should be systematically identified in a manner which would provide for a timely consideration of their importance, i.e., prior to the final specification of an operational system configuration. Where trade-off analyses which include acceptance criteria indicate a machine allocation and means of implementing machine automation which will result in substantial non-acceptance, other methods for increasing acceptance need to be introduced into the system or system support materials, e.g., additional displays might be provided, or attitude change techniques applied, etc. It should be noted that when it is more fully developed, this technique for injecting user-operator acceptance factors into function allocation, display design and software development is applicable to a large number and variety of man-machine systems, and development efforts are therefore legitimately classifiable as basic research.

In summary, Serendipity's approach to the current study of pilot acceptance factors reflects four basic considerations:

1. That explicit and systematic consideration of pilot acceptance factors can and should be carried out within the framework of system requirements analyses undertaken to support function allocation decisions and to establish detailed design characteristics.

2. That pilot acceptance is a function of psychological factors as well as the physical and functional characteristics of particular systems; positive acceptance can, therefore, be established through either system modification or the modification of pilots' perceptions and attitudes toward the system.

3. That careful isolation and analysis of particular acceptance problems is required to identify and apply the appropriate corrective techniques.

4. That techniques developed in the present study for identifying acceptance problems and deriving principles and criteria for incorporating acceptance considerations into functions allocation decisions will generalize to function allocation problems in other automated control systems.

2. METHODOLOGY

An overview of the program for achieving the research objectives outlined in the introduction is presented in flow chart form in Figure 1. Each block represents a major activity or performance requirement in the conduct of the program. In order to indicate the relationship of the effort reported in this document to the over-all program, both current and potential research objectives are represented. Phase 1 is comprised of activities 1 through 4 in the diagram and Phase 2 will encompass activities 5, 6 and 7. The connecting symbol on the output side of activity 7 indicates that, at that point, the program may proceed to a logical continuation of efforts to identify means for establishing positive pilot acceptance of ALS concepts and techniques (Phases 3 and 4), or, as either an alternative or concurrent effort, to proceed with a more basic problem. As indicated, this more basic problem is concerned with deriving generalizable techniques for applying data on human acceptance of automated control techniques to man-machine function allocation decisions.

The general approach and methodology adopted for current and projected research efforts is reflected in the labeling of activity blocks and input/output arrows in Figure 1. A brief discussion follows of the methods employed or which will be required to implement each activity.

2.1 Review of All-Weather Landing System (ALS) Problem

The first activity of the program, as is generally true for any program, was to review the All-Weather Landing System problem in order to determine the basic system requirements and constraints. The present program is not concerned with determining requirements for any particular all-weather landing system, type of aircraft, or era or time. It was intended, however, that the results be practically meaningful and thus the review of requirements and constraints was confined to ALS concepts and techniques which are currently feasible. This led to the

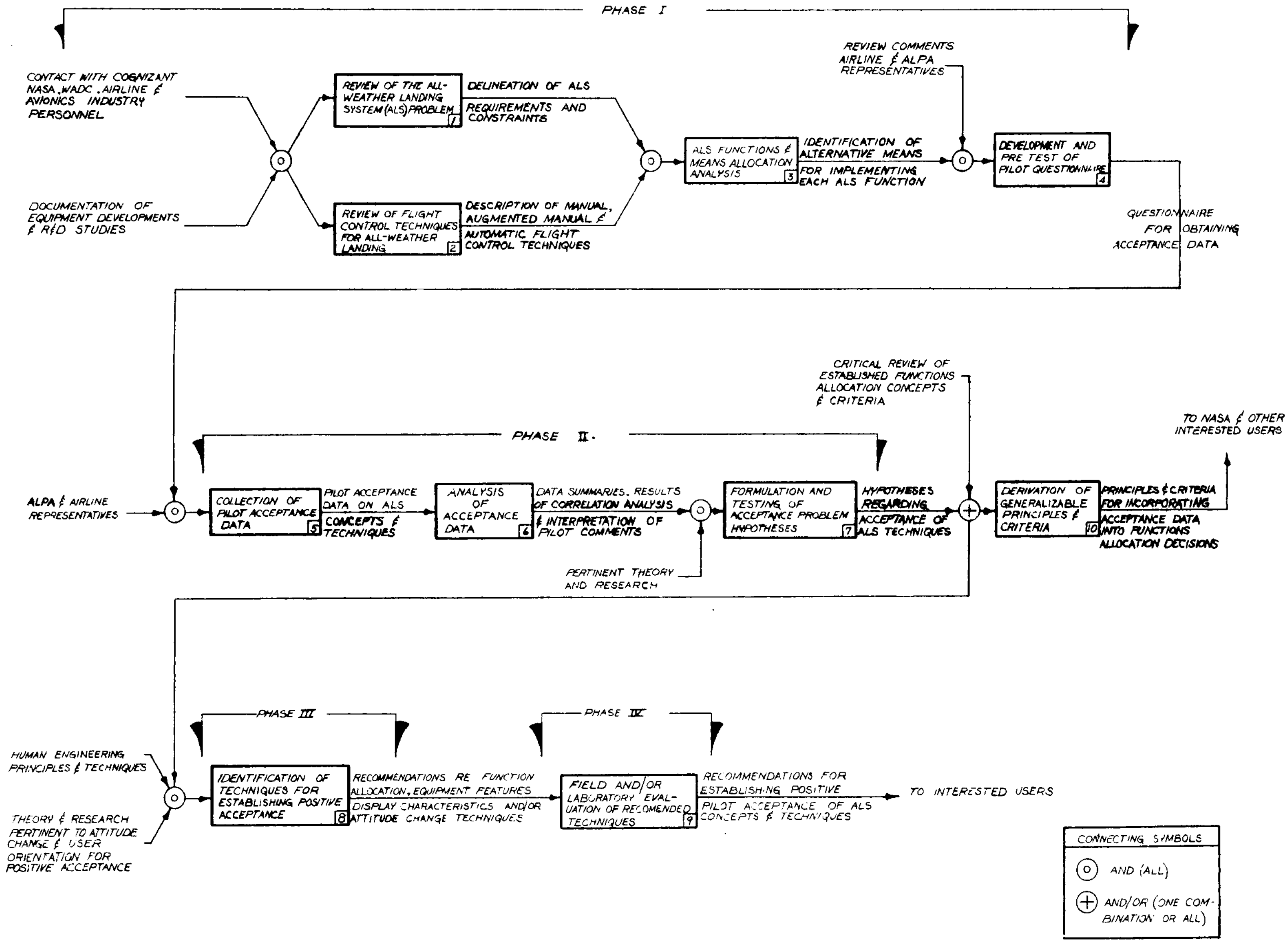


Fig. 1 An Overview of the Program for Achieving Current and Long Range Research Objectives

general assumption that the aircraft and all-weather landing system concepts should be those which are now in existence and/or are deemed feasible for implementation between now and 1975. It was decided that organizations generally concerned with this problem would be the National Aeronautics and Space Administration, the Federal Aviation Agency, commercial airline companies, commercial pilot organizations, military aviation development and operational groups, and avionics industries. Further, it was decided that as much personal interaction as possible was desirable and that it would be necessary to obtain and review a considerable amount of documentation from these sources. A project library system was set up to handle the documentation, and to date, more than 150 references have been received and reviewed. A brief discussion of the interaction with each of the major organizations mentioned above follows.

Coordination with NASA has been maintained by personal contact on approximately a monthly basis since the inception of the program. It is anticipated that monthly coordination meetings will be continued throughout the program.

FAA was contacted and a meeting of cognizant personnel of FAA and Serendipity was convened in Washington, D. C. early in the program. FAA provided information and some documentation of their efforts commencing with project BEACON, a review of air traffic control and a plan for future improvement, which was accomplished by FAA by direction of the President of the United States in 1961. Project BEACON provided the scientific, engineering review and guidelines for the practical long range plan. Accordingly, a system design team was formed within the systems research and development service of the FAA to carry forward the guidelines of the project BEACON report into a detailed and comprehensive system plan. Subsequently, FAA developed a master plan for the "design for the national air space utilization system." A system design team for the landing problem was formed and after considerable research and experimentation issued a specification for an FAA prototype all-weather landing system.

Commercial airlines were contacted and to date personal discussions have been held with representatives of American, United, Trans World, Pan American, and Continental Airlines. These airlines have also provided us with their own plans for reduction of operating minima and their general approach toward all-weather landing under zero-zero conditions.

In addition to the airline companies, contact was made with the Airline Pilot's Association (ALPA), whom we will probably work with in the administration of the pilot questionnaire (see Activity 5). Contact was also made with the International Air Transport Association (IATA), and they provided us with previous and very recent (April 1963) documentation on IATA meetings on all-weather landing systems.

Military groups have done a considerable amount of research and development on their own for all-weather landing techniques. The Air Force has worked directly with FAA on a program mainly concerned with split-axis control and a visit was made to the flight control laboratory of the USAF Aeronautical Systems Division to discuss this program, as well as other research efforts under the cognizance of that laboratory. Reports have also been received from the U. S. Army and U. S. Navy concerning their efforts in all-weather landing but no personal contact has been made with Army or Navy representatives to date.

A considerable number of avionics industry research and manufacturing firms have been contacted, and personal discussions held with many of their representatives as well as a great deal of technical documentation concerning equipment and approaches of the various firms was received.

Utilizing all of the information sources discussed above, a thorough review and analysis of the all-weather landing problem was conducted in order to delineate requirements and constraints for an all-weather landing system and to derive the basic functions necessary in accomplishing an all-weather landing. Each function was further analyzed to derive specific requirements for that function without regard to the means for implementing the functions.

2.2 Review of Flight Control Techniques for All-Weather Landing

Utilizing the same information sources identified in Activity 1 above a systematic review of feasible flight control techniques for all-weather landing was conducted. This review encompassed manual techniques, augmented manual techniques and automatic flight control techniques. A general description of these different kinds of flight control techniques was prepared as an orientation for further research activities and development of the questionnaires. One of the primary efforts of these activities was to establish a means for discussing different roles of participation by pilots in all-weather landings as it was anticipated that many all-weather landing systems will be implemented by combining different flight control techniques for each function.

2.3 ALS Functions and Means Allocation Analysis

The requirements derived in Activity 2 and the flight control technique descriptions produced in Activity 2 resulted in a considerable amount of technical data which would be useful for the entire program and specifically for the development and subsequent processing of the pilot questionnaire. A specific effort was devoted to delineating the system performance requirements associated with each ALS function in as much detail as practicable without describing the means, (i.e., equipment and/or engineering techniques) for implementing the function. The technical data was then organized according to applicability to the functions and events occurring in a generalized landing sequence and prepared as an information appendix. Thus, for each function the technical data was compiled so that various automatic flight control techniques under consideration were described for each function. The result of this activity satisfied one of the intermediate objectives of the program, that is, to have available in a systematic manner the data necessary to question pilots with respect to their opinions and preferences for various techniques or aspects of techniques for accomplishing all-weather landings.

2.4 Development and Pre-Test of Pilot Questionnaire

This phase of the research effort requires the three major steps of developing the questionnaire, identifying the sample, and administering the questionnaire. These steps are described below.

A funneling technique was used for questionnaire development. This method consists of beginning with an investigation of the problem at the widest and most inclusive possible level, using unstructured methods for obtaining information, i. e., interviews and discussions with subjects selected without any attempt to rigorously define the population studied. Consequently, interviews were held with many people in the industry, particularly chief pilots and captains with many years experience. The information gathered by this method permitted the development of more structured interview schedules, thus beginning to narrow the field of information to be investigated as we learned more about the problem and its boundaries. Finally, a preliminary questionnaire was developed and tested on both management and non-management pilots, and on the basis of the difficulties encountered with this preliminary questionnaire another set of questionnaires was developed, again tested, and finally revised to produce the questionnaires contained in Appendix B.

The functions analysis and identification of the means currently being considered for implementing all-weather landing system functions were utilized in the development of the questionnaire to provide the necessary reference for interviewing pilots as to their attitudes toward automation of landing functions. It was this requirement that necessitated the detailed efforts described in Sections 3 and 4 and Appendix A below.

The first problem encountered was that the information gathered on ALS from the literature listed in the references was in an engineering language not always familiar to pilots. Consequently, it was necessary to translate and re-define some of the terms for use in the questionnaire.

A major and more serious problem was uncovered as soon as a trial questionnaire was developed and tested. The pilots were generally unfamiliar with many of the techniques being considered for automatic or semi-automatic landings. Consequently, we were asking them to state opinions and attitudes toward something with which they were not usually familiar. When we attempted to solve this problem by giving them a statement as to what the ALS would be like, it became apparent that their answer would then be simply a re-statement of the assumption we had given them. For example, if we asked them to assume a highly reliable system, they they would say there is no problem (if it really is very reliable). And of course, if we told them that the system wasn't completely reliable, then they said they did not want to use it. It is now apparent that this problem will occur whenever acceptance criteria are to be included in functions allocation trade-off decisions, because it will normally be the case that the majority of operational people will not be familiar with new developmental techniques before they have proceeded to the point of being widely adopted. It also became apparent when working with many pilots that they are not sufficiently familiar with research and development terminology or with engineering principles and electronic hardware to provide a meaningful reaction to technical decisions regarding method of implementing automation.

The solution to this problem is to use a two step method for obtaining the acceptance data and pilot recommendations and critiques. The first step, which is Questionnaire I in Appendix B, is at a general level which will provide meaningful and quantifiable data from all pilots as to their attitudes toward automation of landing functions. This questionnaire was developed on the assumption that the average pilot is not really concerned with nor qualified to give opinions on how a specific black box performs its function. Rather, pilots are concerned with what functions will be automated, what functions are manual, and the interface between manually and automated functions. Furthermore, they are concerned with displays for monitoring automated functions, displays for assisting them in manual functions, and they are very concerned with and have useful opinions on back-up systems which must be used. They are particularly concerned with the manual back-up system which is always assumed, even in the BLEU system (or the pilot would not still be in the airplane). For purposes of manual back-up, they want to know when they will have to assume control in case of a malfunction, how they will detect a malfunction, how much altitude is remaining at this decision gate, etc. It is clear, therefore, that very meaningful information at this level can be obtained from pilots without their knowing or being given extensive technical information on developmental automation methods. For this reason, therefore, the first questionnaire was developed and can be used by all pilots and furthermore it has the advantages of being short, quick to use and easy to tabulate. For these reasons it is assumed that a high level of return can be expected from a mailing of this questionnaire.

In addition, Questionnaire II was developed. This second questionnaire is for those pilots who are more familiar with some of the techniques currently under consideration for automating landings and can therefore give meaningful attitude data as well as recommendations and critiques of these various methods. All pilots will be asked and expected to fill out the first questionnaire, but the second questionnaire will be included only for those who are qualified to answer it, as explained in the letter accompanying the questionnaire (see Appendix B). This separation of the sample into those more and those less familiar with the technical aspects of ALS will attach some prestige to the filling out of the second questionnaire, and should increase the percentage return of this questionnaire.

2.5 Collection of Pilot Acceptance Data

The original intent was to utilize a random sample of line pilots, but at the suggestion of Ames Research Center personnel it was decided to utilize a more knowledgeable and influence leader sample in addition to line pilots in order to obtain both more relevant information on attitudes toward ALS as well as an indication of the direction in which pilot thinking was heading in this area. Consequently, it was decided to split the sample between safety chairmen and line pilots, so that comparisons could be made which would indicate time trends in pilot thinking, as well as the more complete information likely to be obtained from safety chairmen who are more familiar with ALS programs. After discussions with ALPA personnel it was decided to attempt to obtain data on 50 safety chairmen and 50 line pilots. This number is a compromise between the desire for a large sample for statistical purposes and the difficulties and expense in obtaining data from a large number of individuals. The sample will be taken at random from ALPA membership roles so that it will represent the pilots from all sections of the country, all types of airlines, and at all experience levels.

Obtaining the quantity and quality of data desired from a random sample spread all over the country will obviously be difficult. However, it is also necessary as it will be important to be able to both (a) generalize from the data and say "pilots (all pilots) believe . . . ," and (b) to be able to note any marked differences in opinion by section of the country, airline or type of equipment used.

However, in latter phases of the research, when it becomes necessary to obtain additional data from pilots, it will be possible to use pilots flying in and out of Los Angeles. The first, and national, sample will have indicated whether Los Angeles based pilots differ in their attitudes, and if so, what correction to apply to their responses for generalizing to all pilots.

The administration of the questionnaire will be by direct mailing, utilizing ALPA names and addresses. In order to increase the percentage return of the questionnaires and therefore allow accurate generalization to the total population of pilots, a follow-up letter will be sent out to increase the number of returns, and this will eventually be followed by a long distance phone call to those still not returning their questionnaire. The phone call will be used to clarify any misunderstandings or problems and should result in a very high total return rate.

2.6 Analysis of Acceptance Data

The questionnaire data will be coded on data summary sheets, with this operation done independently by two clerks and the results checked to remove the inevitable errors. The data will then be reduced in two major steps, as follows:

The first step will consist simply of summing the data on the acceptance level of automation by function, by means of automation, and provisions for back-up, with the number of pilots pro and con and the percentages indicated in tabular form. In addition, pilot comments and recommendations will be categorized, summarized, and also presented in table form. This first data presentation step, therefore, will be a simple presentation of the extent and location (by function) of the acceptance problem, plus pilot recommendations for improvement.

The second step will consist of a more sophisticated and intensive study of the data to uncover those factors related to acceptance problems in order to permit their later removal through either system modification or training. This step will, therefore, consist of the identification of all possible factors (independent variables) such as geographical area, size of airline, type of equipment (jet or prop), pilot experience, knowledge of ALS, instrumentation available to pilot, etc., which may be predictive of acceptance of ALS. These factors will then be statistically related to all possible acceptance factors (dependent variables) such as level of automation by function, means of proposed automation, acceptance variation by addition of displays and type of displays, etc.

Relatively simple statistical techniques will be used, such as $\underline{t}$ tests, chi squares, rho, and Pearson $\underline{r}$. These techniques will be used because of the unequal n's which will undoubtedly occur in the areas and categories to be explored, and to permit the use of maximum human judgment and experience in exploring the data by hand calculators. However, interactions, i.e., multiple or dynamic relationships will be sought as this will permit the ferreting out of hidden, unexpressed or even unconscious factors affecting acceptance.

In a new area of investigation of this type the first analysis always reveals surprises, with some unexpected factors appearing to be important and other factors assumed to be important appearing to have little or no significance. These preliminary results will be discussed with experienced pilots, and, utilizing their counsel, the data will be re-analyzed and re-coded where this appears indicated or further explored where other hypotheses are suggested, until both our scientific and pilot personnel and advisors feel that all possible relationships have been uncovered. This extensive analysis and re-analysis, and the development and use of additional and combined measures and ratios and further analyses will uncover relationships not found on the first run. However, the question will then arise as to whether or not the results obtained are in fact real findings or spurious results due to the excessive digging and squeezing of the data until chance relationships have been obtained. This situation leads to a distorted outcome referred to by statisticians as Type I error, i.e., if enough factors are investigated a large number of significant but not necessarily valid relationships will be found due to the large number of possible relationships involved. An example of this is the economist who found a "significant" relationship between the number of letters in the names of the states in the United States when listed in alphabetical order, and the annual production of potatoes in the provinces of China similarly arranged. However, without a thorough analysis of this type it is not possible to find the unexpected and invisible relationships that only a statistical analysis can provide. For this reason the sample of pilots will be sub-divided at random into two samples, with the first exploratory analyses performed on a sub-sample. After these analyses, as described above, have been completed a second analysis will be performed on the second sub-sample. This second analysis will be used to cross-validate the relationships found in the first analysis.

In this second analysis rigorous statistical rules will be observed so that the relationships found in the first analysis which again occur can be considered reliable and thus produce confidence that they will hold in the future. There will, however, be some shrinkage in this second analysis, i. e., some of the relationships found in the first analysis will disappear having been due to chance relationships. The final tabular presentations of the data will, however, include the total sample studied.

This type of repeat analysis avoids the error of ignoring results that at first appear insignificant but may be real (a Type II error), as well as protecting against spurious results, or Type I errors, and will uncover relationships not obvious in a case study approach to acceptance. Finally, the completed statistical analyses and their apparent meaning will be discussed with personnel from the Ames Research Center, ALPA, the airlines, interested pilots who have been cooperating with on the project, etc., so that the results can be discussed and presented in the report in language that is understandable and meaningful to pilots and members of the industry. These discussions will undoubtedly lead to suggestions for additional tables and graphic presentations and possibly some additional analyses for presentation purposes.

2.7 Formulation and Testing of Acceptance Problem Hypotheses

The analyses conducted in Activity 6 will provide a comprehensive and detailed discussion of pilot acceptance of ALS concepts and techniques. However, in order to apply these acceptance data to the development of techniques for establishing positive acceptance, it will be necessary to adopt a set of explanatory hypotheses with respect to the sources of any negative acceptance expressed in the data and to the anticipated effect of various corrective techniques.

To a large extent these hypotheses will be suggested by the results of the preliminary analysis of questionnaire and interview data. Insofar as the data allow, some testing of these hypotheses will be accomplished through the repeat analyses discussed in Activity 6. In other instances, it may be necessary to obtain new data through follow-up questionnaires or additional interviews, using a procedure designed to obtain information which will support or disconfirm the hypotheses.

Where it is necessary to go beyond the data available research studies and project reports will be explored in order to identify or evaluate useful hypotheses. Emphasis will be on deriving a set of statements, supported to some extent by the data obtained in the present study and/or available literature, which will provide a sound basis for identifying techniques for establishing positive pilot acceptance of ALS concepts and automatic control techniques.

2.8 Identification of Techniques for Establishing Positive Acceptance

The identification of this activity as a program for performance requirement is predicated on the assumption that the data collection and analysis activities described earlier will, in fact, reveal potential low or negative pilot acceptance of certain ALS concepts and techniques. These problems and the hypotheses formulated in Activity 7 will be processed in this activity to develop recommendations for the development, testing and application of techniques for establishing positive pilot acceptance.

The first step in the implementation of this activity will be to classify each potential acceptance problem as resolvable through equipment modification, modification of operating concepts, re-allocation of man-machine functions, or modification of pilot attitudes. Criteria for this classification will be derived from the anticipated impact of particular acceptance problems on system utilization and reliability, the availability and potential effectiveness of corrective techniques, and the feasibility and costs of applying alternate techniques.

As indicated in Figure 1, two primary sources of information will be utilized in the identification of these techniques: (1) established human engineering principles and (2) available research data and theory pertinent to the acceptability of various function allocation decisions and to attitude change techniques. Based on these inputs, recommendations considered appropriate to each potential acceptance problem will be derived. Human engineering recommendations will be considered for problems attributed to unacceptable provisions for pilot monitoring, override control, etc. Special emphasis will be placed on identifying display requirements and characteristics which are expected to foster pilot acceptance. Recommendations for the development of attitude change techniques will be based largely on available and pertinent social psychological research. Techniques which have been successfully employed in overcoming negative attitudes and resistance to change in military and industrial settings will be appraised for applicability to pilot acceptance problems.

It should be noted that it will be necessary to consider two major aspects of the potential acceptance problem. One reflects an acceptance situation wherein a control technique or equipment system has been adopted and consideration is effectively limited to design features, such as display characteristics or the provision of additional displays which would not otherwise be required but should be incorporated in order to achieve or enhance pilot acceptance. The second acceptance situation is expected to provide for consideration of potential acceptance problems at an earlier stage of system development. Techniques for avoiding serious acceptance problems could then be extended to those influencing operational employment concepts and the allocation of functions to men and machines. Both situations, of course, are open to the application of pilot orientation and attitude change techniques.

2.9 Field and/or Laboratory Evaluation of Recommended Techniques for Establishing Positive Acceptance

Techniques for establishing positive pilot acceptance will be based on the analyses described above and on hypotheses regarding system design features and/or psychodynamic processes which are assumed to underly overt expressions of low acceptance. In most instances the effectiveness of these techniques in producing higher acceptance will not be known. Prior to their application, then, some attempt must be made to determine their value. Activity 9 would, therefore, be concerned with testing the effects of specific system design changes on the application of recommended attitude change techniques to low pilot acceptance.

The extent to which such tests would be carried out would be determined on the basis of the quality of information already available for estimating the effectiveness of various techniques and on the costs and feasibility of obtaining better information. A modest evaluation effort is envisioned wherein useful information would be obtained through the use of opinion survey questionnaires and observation of the reactions of formerly negative pilot groups to recommended design changes. Alternative solutions for acceptance problems would be presented to potential system users in a manner which would enable investigators to rank them in terms of acceptance.

The proposed study is also expected to lead to the identification of test and evaluation problems which are best resolved in a series of laboratory studies or field evaluations. In these instances, recommendations would be prepared regarding the design of such studies and their implementation using Ames Research Center facilities and/or in subsequent field research projects.

2.10 Derivation of Generalizable Principles and Criteria

The identification of this activity as a potential area of concern in the research program follows from the assertion in the introduction that the approach and techniques being developed in the present study should be applicable to control systems other than the all-weather landing systems currently under consideration. It is anticipated that present efforts to obtain and evaluate pilot acceptance data and subsequent attempts to assess the impact of various function allocation decisions on acceptance will provide a basis for identifying general principles and criteria for incorporating acceptance factors into function allocation decisions.

The refinement of methods for isolating significant considerations and systematically applying them to decisions made during the allocation of functions to men and machines is an ongoing concern in engineering psychology. Established concepts and working principles for allocating functions derive largely from early attempts to compare men and machines in terms of performance capabilities. The resulting orientation is that men compete with machines for various system tasks and that functions should be assigned only on the basis of relative superiority in meeting performance requirements. An alternative view is that men are not comparable to machines, they are complementary, and consideration shifts to how men and machines should be combined to implement system activities. This latter view examines activities that can be performed by both men and machines and goes beyond a consideration of relative performance capabilities in determining task assignments. Such factors as flexibility in man-machine interactions, and problems of "responsibility," "authority," "primary vs. back-up control," and "operator motivation" are included.

In view of current and projected computer capabilities, it is asserted that the latter view is more suitable for resolving functions allocation problems in systems employing automatic devices. Activity 10 would thus be carried out within this framework. As indicated in Figure 1, the first step would consist of a critical review of established concepts and principles pertinent to function allocation decisions for automated systems. The implications of omitting a consideration of system user/operator acceptance would then be examined to establish additional requirements and constraints for function allocation activities. Then, based on the experience gained in the present study in identifying acceptance problems and developing hypotheses relevant to their occurrence and resolution, the general manner in which acceptance data could be obtained and processed to meet these requirements would be identified.

An example of a generalizable principle related to the collection of acceptance data in a form that is useful for assessing the impact of various function allocation decisions on acceptance is provided above in Activity 4. In developing the questionnaire, it was found that many pilots were not sufficiently familiar with engineering techniques under consideration for ALS applications to provide acceptance data on technical decisions regarding the implementation of system functions. However, they expressed a vital interest in the particular functions for which automation is being considered and in their role in monitoring or overriding automatically controlled functions. A generalizable principle which emerges from this observation is that acceptance of the user/operator's role in the system should be directly explored rather than attempting to obtain reactions to particular hardware items or engineering techniques from the general operator population.

The implementation of Activity 10 would thus consist of a systematic abstraction of general principles and criteria which would provide guidelines for collecting acceptance data and applying them in function allocation decisions. These principles and criteria would be derived from experience gained in the present study of acceptance factors in ALS development and from a critical review of established function allocation concepts and working principles.

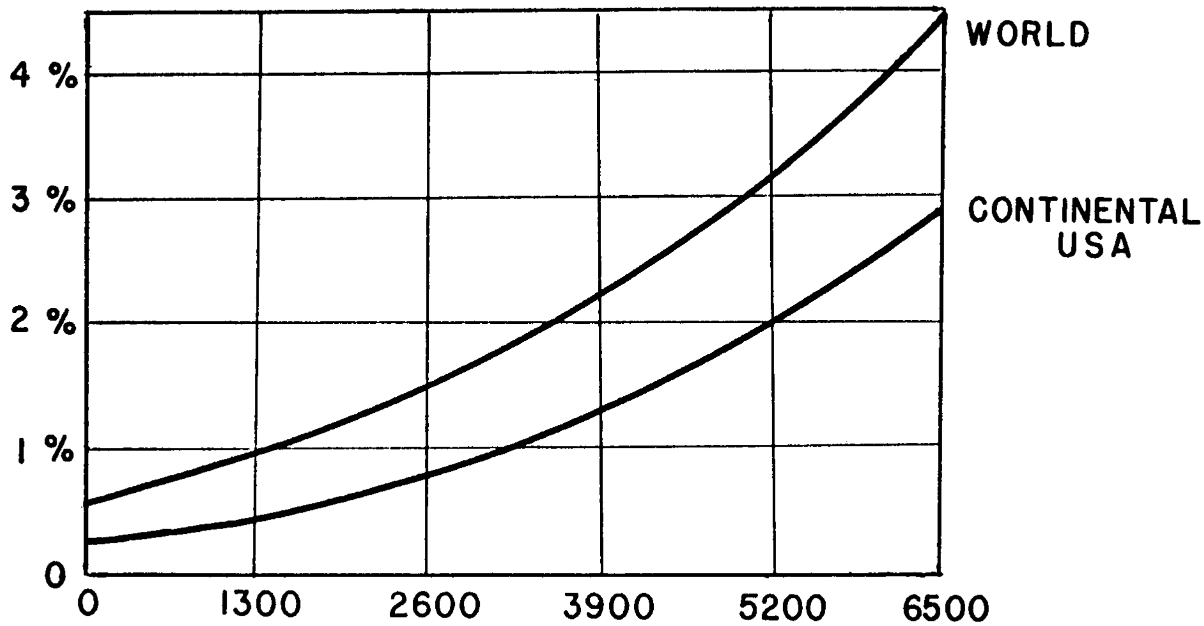
3. THE ALL-WEATHER LANDING PROBLEM

The term "all-weather landing" is one of the most frequently used terms in aviation today but it might better be called the "all-weather landing problem". There is little agreement on what all-weather landing means but there is unanimous agreement that it is, indeed, a problem that must be solved. Generally speaking "all-weather landing" implies the execution of an approach and landing without limitation insofar as local weather and/or airport visibility conditions are concerned. This section of the report discusses some of the implications and generally agreed upon objectives of all-weather landing, the IATA program for progressive reduction of minima toward all-weather landing operations, and the basic requirements for an all-weather landing system.

3.1 WEATHER AND IT'S IMPLICATIONS

Weather is costly; in fact, the more weather there is the more costly it is for commercial airline operators. A solution to the all-weather landing problem could have many beneficial effects such as improved customer relations and increased safety as well as reducing airline operating costs. The impact of a solution can probably be more dramatically illustrated by considering the economics involved.

Commercial airlines are currently authorized to operate in terminal weather conditions of 300 foot ceilings and/or three-quarter mile visibility at some airports and 200 foot ceilings and/or one-half mile visibility (under some specific conditions to be discussed later) at other airports. Figures 2 and 3 provide an indication of how frequently weather conditions below authorized minima occurs. Figure 2 illustrates the percentage of occurrence of various visibility conditions at U. S. and International terminals; Figure 3 illustrates



Runway Visual Range - Feet

Fig. 2 Percentage of Occurrence of Low Visibility Conditions at United States and International Terminals

(Taken from Reference 24)

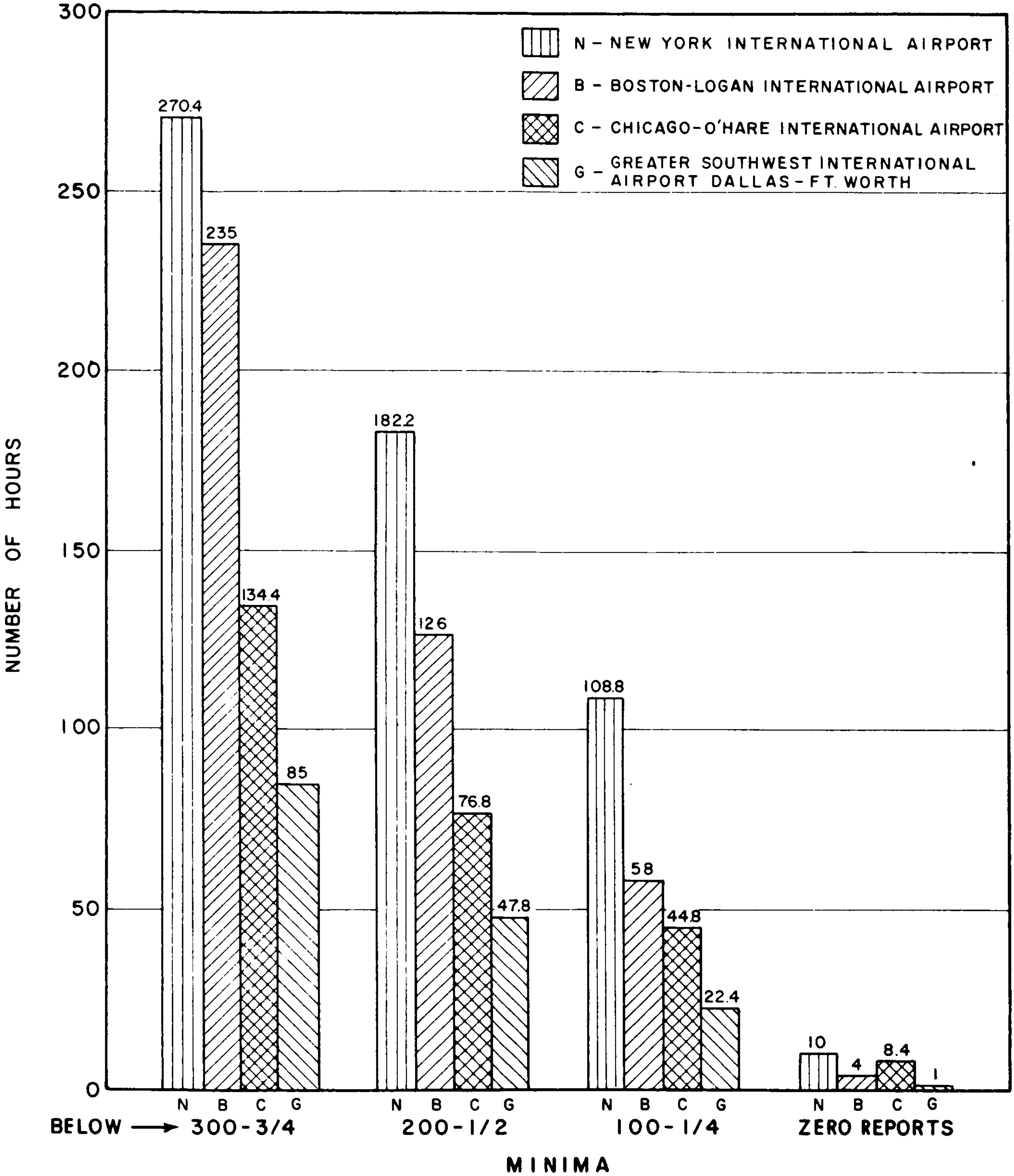


Fig. 3 Average Yearly Hours Below Landing Minimums - Including Zero-Zero Reports

(Taken from Reference 6)

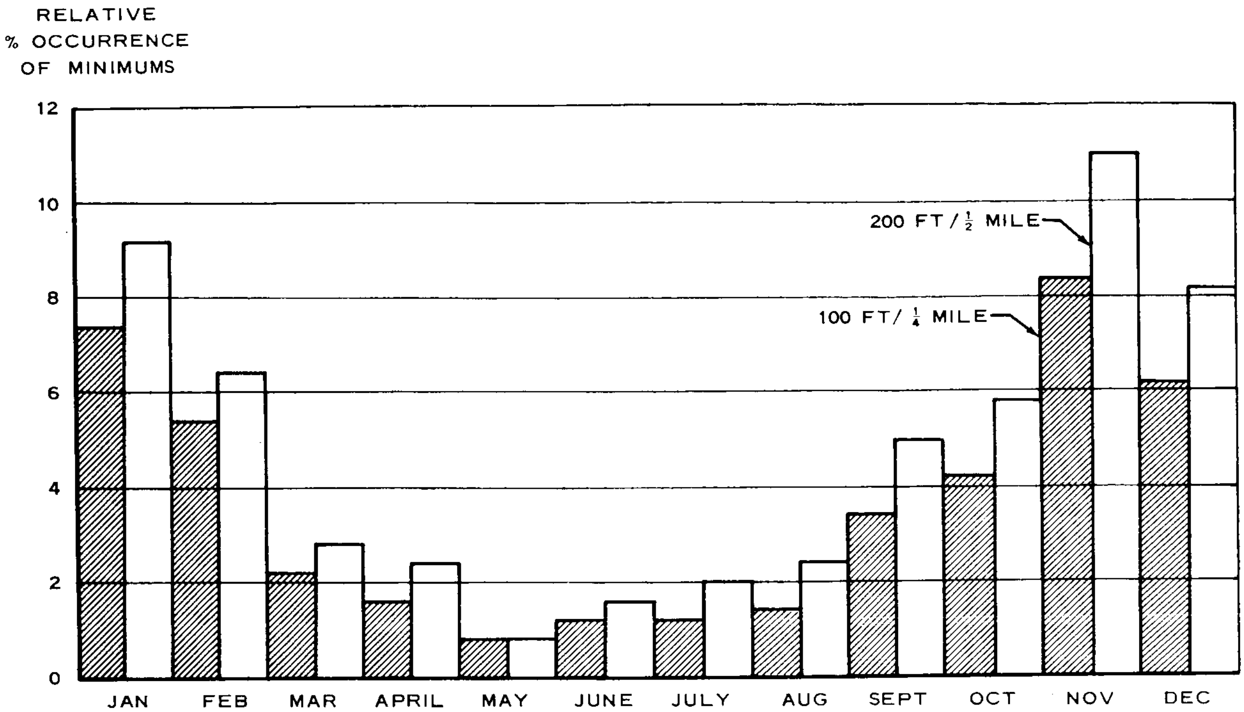


Fig. 4 Percent of Occurrence of Minimums at a Representative Continental U. S. Airport

(Taken from Reference 22)

and compares the minima data for four widely scattered airports in the U. S. over an average year (the data were averaged over a five year period from 1957 to 1961). Figure 4 illustrates the relative frequency of 200 feet-1/2 mile and 100 feet-1/4 mile conditions and thus indicates the percentage of flight cancellations. From these data it can be shown that a system which can be certified and actually operated by the airlines to 100 feet-1/4 mile will cover about 57 percent of the cancellations and thus produce marked improvement over 200 feet-1/2 mile minima. The average cost to the operator for a typical airport closed due to weather and forcing the airline to land at an alternate has been reported to follow the trend of increasing dollar costs shown in Figure 5. A more detailed discussion of such costs is contained in a recent TWA report (28) and is excerpted below to illustrate the actual costs incurred when weather is below established minima.

> "An FAA Document AD264821, dated March 1961, and entitled, 'Forecast of Losses Incurred by U. S. Commercial Air Carriers Due to Inability to Deliver Passengers to Destination Airports in All-Weather Conditions: 1959 - 1963', provides a basis for estimating the cost to TWA of failing to achieve all-weather operational reliability. This study forecasts that U. S. airlines, considering only domestic operations, will suffer losses totaling $67.7 millions in 1963 for this cause. Based upon the comparative tabulation of data for the five year period covered, these losses increase at the rate of approximately 10% per year, somewhere near coinciding with the rate of market growth. By projecting this rate, estimated losses in this category will approach $90 millions annually by 1966 unless progress is made in reducing the operational exposure to low minimums irregularity.
>
> "A basic parameter used in computation of the statistics in this document was a survey of the number of instrument approaches executed during the year at each of 22 representative airports. Since the document was issued in March 1961, it was necessary to project these statistics through 1963 for the report. A comparison of the estimated total number of instrument approaches for the

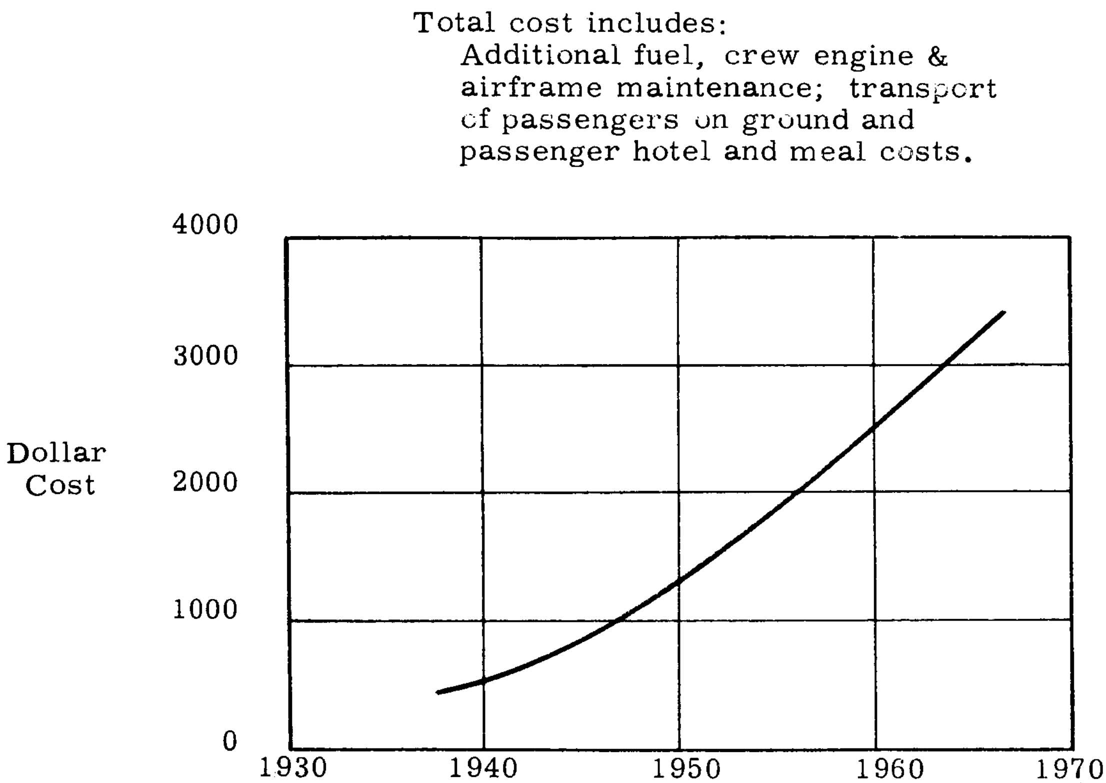


Fig. 5 Trend of Diversion Costs Due to Weather Below Minimums

(Taken from Reference 22)

year 1962 against the actual number recorded by the FAA at this group of airports is within 1%. It is therefore considered that the accuracy of forecast of this document warrants its use as a yardstick in estimating the economic impact of all-weather goals.

"The estimated 1963 losses to the industry of $67.7 millions contains three general categories, all of which are well based, but two of which account for the indirect losses involved in landing accidents caused by lack of all-weather capability and losses in revenue due to decreased demand as an influence of weather limitations. These losses are valid factors for consideration in the long-term accounting for the cost of doing business and amount to $47.2 millions of the total. $20.5 millions represents the direct cash costs of flight delays, cancellations, and diversions, and can be applied against the cost of an all-weather capability program to analyze for short term pay-out. During the five year period studied, this category of costs increased at an average rate of nearly 15% per year; therefore, these annual costs because of lack of all-weather capability are estimated at $31.2 millions by 1966."

While it is quite evident that there is a substantial loss of revenue due to operational irregularity as a function of terminal weather conditions, there are also cost factors involved in reducing minima and achieving all-weather capability. It is impossible to specify these costs at this time, but there will certainly be extensive costs for equipment modifications, evaluation and installation of new equipment, and additional flight training to qualify pilots for the new equipment and conditions.

3.2 REDUCTION OF MINIMA

ILS operating minima for U. S. civil aircraft have been established at 200 foot ceilings and one-half mile visibilities for many years. When the commercial jet transport was introduced into airline service in 1958, landing minima of 300 feet and three-quarter mile were established by the FAA for the jets. Early in 1962, 200 feet and one-half mile minima were authorized for turbo jet aircraft if special conditions (i.e., pilot training, aircraft instrumentation, monitoring facilities, runway extension, etc.) were met. Since the problem of reduction of minima has become increasingly more important and is obviously necessary in an evolution towards all-weather landings, concerted efforts have been undertaken by various organizations, agencies, and airline companies to establish the basic objectives for reduction of minima and to set up systematic programs for accomplishing these objectives. This section of the report discusses these objectives and outlines the programs for their accomplishment.

3.2.1 IATA Requirements for a Three Phase Reduction of Minima

IATA has established a three phase program for the evolution of all-weather landing capabilities in commercial operations. These three phases are generally accepted and followed by IATA members and the FAA. The three phases have been described by IATA (17) as follows:

"Phase 1 - Operation of Jet Aircraft to Minima now applicable to Piston-engined Operations.

" i) Minimum values in current use for propeller-driven aircraft are generally 200 feet ceiling and half-a-mile visibility. Their universal application to large jet aircraft is an immediate airline objective. Ground installations which now provide reliable and stable guidance are considered satisfactory for Phase 1 operation with large jets.

" ii) Any ILS guidance difficulties which prevent use of these limits by jet aircraft at certain airports are considered a local problem and not necessarily a basic system limitation. To eliminate such local problems, improved azimuth guidance of high stability is urgently needed, such as that provided by Performance Category II ILS localizers.

"Phase 2 - Reduction of Present Operating Minima for all Aircraft Types.

" i) This phase, which airlines would enter as soon as practicable, involves certain ILS system improvements to enable safe and routine non-visual penetration below 200 feet. This degree of precision guidance will generally require a fully automatic or semi-automatic approach, transition to visual reference and manual landing.

" ii) Introduction of lower minima should occur progressively in operationally proven stages. The minimum ceiling and visibility values marking the lower limits of Phase 2 must be ultimately determined by actual test and operating experience.

"iii) Although precise operational values cannot, and need not, be determined at this time, it is desirable that suitable Phase 2 target values, associated with recognised ceiling and visibility increments, be adopted as system design criteria. Consequently, values of 100 feet ceiling and 1/4 mile visibility have been selected in defining the approximate lower limit of this Phase.

" iv) ILS system improvements for this Phase (Performance Category II ILS facility) should provide reliable, stable radio guidance down to an on-glide path height of about 50 feet. Continuation of the automatic approach to this height should be a system capability although visual reference may have been established at a height of 100 feet and the pilot has determined that the approach is proceeding satisfactorily. A primary requirement is improved azimuth guidance of high stability and integrity to -

a) ensure smooth, accurate tracking of the aircraft along the extended runway centre line, and

b) eliminate the need for subsequent visual correction of lateral displacement.

" v) In addition, the accuracy and stability of the vertical guidance provided by the glide path system should be improved to the extent required by the mode of operation and the techniques applied. Finally, positive height/distance checks should be available. It is preferable that marker beacons be located at specific, operationally significant points which favour the pilot's decision-making process during successive transition phases.

"Phase 3 - Safe and Regular Operation in All-Weather Conditions.

" i) This phase, representing the ultimate airline objective, probably involves fully automatic or assisted landing techniques. Appropriate system characteristics and flight techniques for ground and airborne components are under active study by administrations, research establishments and airlines. Further research and extensive operational testing are required to determine that azimuth guidance, suitable for automatic landing, is within the capability of the ILS technique."

3.2.2 ICAO ILS Facility and Operational Requirements

Closely related to the IATA objectives for an all-weather landing program are the requirements established for ILS evolution. These requirements are specified in the following facility performance categories which were adopted by the ICAO 7th COM DIVISION meeting on January 9 - February 9, 1962 (26).

"Facility Performance Category I - ILS An ILS which provides guidance information from the coverage limit of the ILS to the point at which the localizer course line intersects the glide path at a height of 60 metres (200 feet) or less above the horizontal plane containing the ILS reference point.

"Facility Performance Category II - ILS An ILS which provides guidance information from the coverage limit of the ILS to the point at which the localizer course line intersects the glide path at a height of 15 metres (50 feet) or less above the horizontal plane containing the ILS reference point.

"Facility Performance Category III - ILS An ILS which, with the aid of ancillary equipment where necessary, provides guidance information from the coverage limit of the facility to, and along, the surface of the runway.

"Operational Performance Category I: Operation down to minima of 60 metres (200 feet) and 800 metres (2600 feet) visibility with a high probability of approach success.

"Operational Performance Category II: Operation down to minima below 60 metres (200 feet) and 800 metres (2600 feet) visibility and to as low as 30 metres (100 feet) and 400 metres (1300 feet) visibility with a high probability of approach success.

"Operational Performance Category III: Operation down to and along the surface of the runway unrestricted by cloud base and visibility conditions with a high probability of landing success."

Figure 6, which was taken from a Pan American Airlines program report (24), is a representation of the performance characteristics of a typical ICAO, Category II, Instrument Landing System.

3.2.3 Program for Accomplishing Phase I Objectives

Several major airlines now have FAA approval for Phase 1 operations, i.e., weather minima at 200 and 1/2 with a 2600 foot runway visible range (RVR). These authorizations have been granted for specific airports and specific airline pilots. Present Phase 1 operations are based on a control procedure wherein flight directors provide the pilot with pitch and roll steering commands to an altitude of 100 feet. At this point, a transition to contact conditions must be achieved and the landing is accomplished by visual reference or, if this cannot be done, a missed approach is executed.

Approval for Phase 1 operations is subject to the following constraints:

1. Airports

   a. 200 and 1/2 was initially authorized for New York Idlewild, Los Angeles International, Paris Orly, and London Heathrow airports. Additional approval has been extended for Baltimore, Philadelphia, Detroit, Chicago, and San Francisco.

   b. Authorization was confined to those runways served by ILS and Precision Approach Radar (PAR).

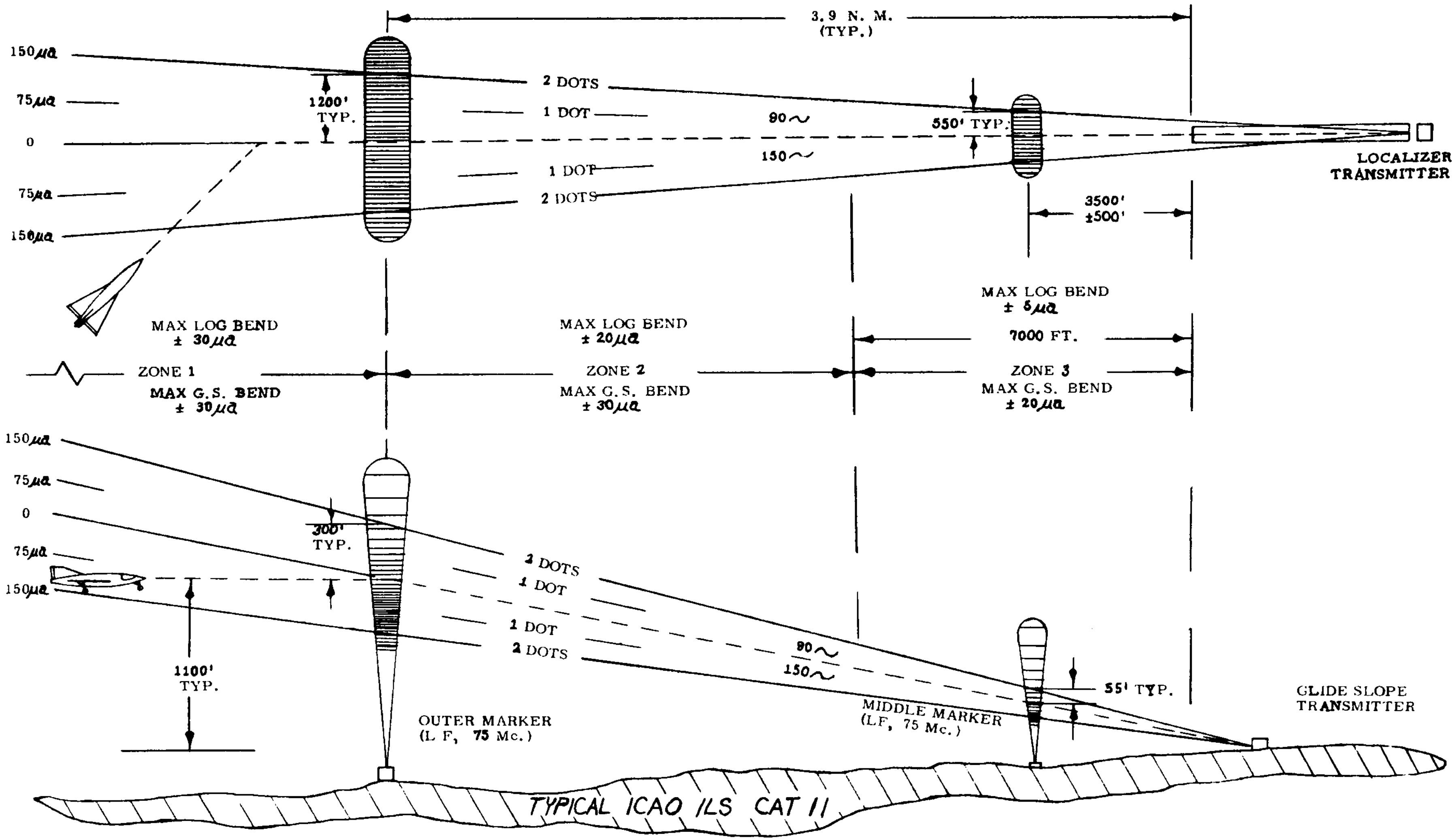


Fig. 6 Performance Characteristics of a Typical ICAO Category II ILS

2. Operation

a. Use of the flight director as the primary guidance reference was required.

b. Monitoring of PAR during the approach was required (now deleted).

c. Required runway length increased over CAR minima by greater of 15% or 1000'.

d. Crosswind component could not exceed 10 kts.

3. Pilots

Captains were individually authorized by the FAA to utilize 200 and 1/2 minima following completion of a training program and check-out. The training program which qualified the Captain for 200 and 1/2 included the following demonstrations:

a. A hooded approach, to 100' using the flight director; from this altitude, the pilot would either be required to land or to execute a missed approach.

b. A hooded approach to 100' with the autopilot coupled to the ILS and a manual landing by visual reference.

c. A hooded approach to 200' using displacement instrumentation (non-computed) reference only, with either a landing or missed approach executed from this altitude.

3.2.4 Program for Accomplishing Phase 2 Objectives

The airlines and the FAA are seeking a practical approach that will permit safe and reliable Phase 2 operations, that is, landing minima of 100 and 1/4 and an RVR of 1300 feet. In application this means that as long as 1300 feet RVR exists the ceiling may be reported as indefinite and an approach to landing may be executed so long as the pilot has the runway lights in sight at the 100 foot point. It should be emphasized that Phase 2 requires that flareout, touchdown and roll-out will be accomplished manually by the pilot with visual reference. Since the transition from instrument to visual reference will be required, it is necessary that this transition occur during the period in which a successful overshoot can be accomplished. This minimum missed approach altitude is not firmly established but is generally accepted as 100 feet and has been designated the decision gate. Thus, a necessary corollary to Phase 2 operations is positive identification of the decision gate or 100 foot altitude in order to make a go-around decision. At least three methods are under consideration for identification of this point:

(1) Altitude information from the radar altimeter.

(2) Incorporation of DME readouts with ILS displays. The problem of display of DME information has not been settled, and some manufacturers are considering showing the information on the flight director for the last two miles of range.

(3) Re-introduction of the inner marker to indicate the 100 foot altitude point.

Because of the increased stress induced during Phase 2 operations, due to poor visibility conditions and less time to make a missed approach decision, much consideration is being given to relieving pilot workload and requirements for the performance of routine tasks in order to make more time and improved facilities available to him for monitoring and assessing the flight situation. The following techniques have been considered:

(1) Utilization of an automatic pilot to maintain lateral control until approaching time for flareout. The pilot remains in the primary control loop and retains pitch and airspeed control. This establishes a good situation for glide slope smoothing and phasing into a pilot-controlled flareout and touchdown.

(2) Automatic airspeed control during approach and landing.

(3) The use of computed information for an optimum visual display of pitch command and pullout, whether using the autopilot or the flight director.

3.2.5 Program for Achieving Phase 3 Objectives

The requirements for Phase 3 operations have not been fully determined. Generally, Phase 3 is oriented toward approach and landing under "zero-zero" weather conditions and this could mean landing, touchdown and roll-out without visual reference, i.e., "blind landings". The extent to which visibility can be degraded, however, is not universally agreed upon and some airlines are assuming that Phase 3 operations will retain some sort of "see to land" concept. It does seem true, however, that in Phase 3 operations the aircraft will be committed to land before visual contact is established and that no ceiling limitations will be involved in the authorized weather minimums. However, if the pilot will be required to obtain visual guidance from runway and taxiway lighting for manual control of the landing roll-out and taxi operations, then some minimum visibility will be necessary. Studies have indicated that a pilot can satisfactorily control an aircraft through a landing maneuver provided that his alignment is good and he can see the distance over which his aircraft will travel during the next three seconds. For typical jet touchdown speeds this is equivalent to an RVR of 700 feet, and this appears to be the lowest minimum that can be considered for a "see to land" type system. It also seems true that some type of fully automatic landing system or display system providing automatically computed information will be required. Phase 3 operations will also require augmented glide slope equipment and flareout computers.

Although the landing will be made without visual reference and may be completely executed under automatic control, a decision gate may still be necessary which will allow the pilot to take over and execute a missed approach if the aircraft is not, at that point, in an alignment condition considered satisfactory for completing the landing. It is assumed that aircraft altitude at the decision gate will still be in the vicinity of 100 feet. The difference between Phase 3 decision gate requirements and Phase 2 decision gate requirements is that the relationship of the aircraft to its intended touchdown point must be evaluated from cockpit displays rather than visual reference.

While it is conceivable that automatic control systems could be developed in the future which would land aircraft under truc zcro-zcro conditions, there are some practical limitations which must be considered before the aircraft is landed under conditions in which "you can't see your hand in front of your face". These considerations revolve around the vehicular and personnel movement around the ramp area that is necessary to support an airline operation. Provisions must be made to continue this support without increased hazard or decreased efficiency. Furthermore, since a passenger's destination is rarely the airport itself, surface transportation to and from the airport must be able to provide reliable traffic flow. Major disruptions in the services for getting the passengers to the airport and from the airport is as severe an all-weather inadequacy as is the inability of the aircraft to take-off or land. One airline has suggested that there must be a minimum of 200 feet RVR for the aircraft to land and the complementary airport operations to be carried out. Furthermore, it must also be remembered that all-weather operations cannot really mean <u>all</u> weather conditions as it is obvious that aircraft will not attempt to land during hurricanes, tornadoes, gales, etc. All-weather really means extremely low visibility with crosswinds not exceeding 10 miles per hour.

A study made of conditions which create visibilities below established IFR minima has identified five types of airport weather producing this effect:

1. Dense fog
2. Low cloud ceilings
3. Heavy smoke
4. Heavy precipitation
5. Blowing snow or dust

Dense fog does not exist where the wind is above 6 mph. This condition produces zero ceiling and visibility and is, by far, the biggest factor preventing normal landings from an instrument approach. It should be noted that a crab angle would be negligible at these wind velocities. Low cloud ceilings are most prevalent when the winds are below 10 mph. Again, the crab angle is no problem. With the third condition, heavy smoke, the horizontal visibility could be extremely limited, but the vertical visibility is sufficient for crab removal. Precipitation, snow and blowing dust, like smoke, permit vertical visibility for recovery from a crab angle.

3.3. ANALYSIS OF LANDING REQUIREMENTS

It should be emphasized that the ultimate objective of this research program is to identify generalizable principles and criteria for incorporating user acceptance data into criteria for the allocation of functions in man-machine systems. The more specific objective of the current program is to identify pilot acceptance criteria for all-weather landing systems. In order to meet both the ultimate objective and the specific objective it is necessary to obtain, analyze and verify data about the problem at a level of detail that is meaningful for both of these objectives. Thus, for example, if the study were concerned only with obtaining, analyzing, and verifying data on whether automatic landing systems are acceptable as a whole, neither of these objectives could be met. In order to achieve both program objectives, the research problem must be partitioned into a series of smaller research activities wherein acceptance data is collected, analyzed for both practical and statistical significance, and used as a basis for the hypotheses and principles concerning acceptance criteria. Further, since we are now concerned with man-machine allocation and pilot acceptance of various allocation decisions, the subdivision of the total problem must be accomplished in terms of system performance requirements. In brief, this means that the functions which the system must perform in order to meet operational objectives must be identified without regard to the means under consideration for their performance. Further, it is necessary to identify the constraints within which these functions will be implemented, since we are not dealing with a hypothetical system for air transportation but are concerned with requirements for all-weather landing in operationally feasible, high performance commercial aircraft. We are thus confronted with constraints on the system as a whole, for example, flight control will be effected by conventional aerodynamic control surfaces. Finally, we are only concerned with those aspects of the landing functions in which it is feasible for pilots to make control decisions and/or perform control actions for implementing these decisions.

This section of the report presents a discussion of the basic requirements for an all-weather landing system, and the functions and events which define a generalized landing sequence. Performance requirements and constraints associated with each general function in the landing sequence are identified.

3.3.1 Basic Requirements and Constraints for an All-Weather Landing System

The requirements for an all-weather landing system can only be expressed generally at present. These requirements will become more specific as constraints on all-weather landing system developments become more specific. In fact, it is hoped that the results of this study will delineate certain constraints in terms of pilot acceptance which will contribute to the derivation of more specific all-weather landing system requirements. The requirements presented below are considered to be basic but are not presented in great detail. Several studies have been accomplished which go into considerable detail concerning the requirements for all-weather landing systems and the advantages and disadvantages of various concepts for implementing these requirements. A set of statements reflecting general requirements and constraints has been collected from these sources and are re-stated below.

1. The most general requirement for an all-weather landing system is to acquire or initiate control of an aircraft from an approximately known position in the vicinity of an airfield to a precisely known position on the surface of a runway along a path that terminates in a safe attitude, speed, and direction of travel.

2. The system should be relatively independent from local terrain features and the availability of real estate.

3. Reliability is of obvious importance but not of immediate concern. Reliability figures on the order of 1 in 10^7 have been suggested.

4. The system must be acceptable to the pilot and pilots must have sufficient confidence in the system to accept the system for going "all the way in" with the same confidence as he now has in his visual landing procedure.

5. The pilot must be able to assess the performance of any all-weather landing system whether it be one in which he is a primary element of the control loop or one in which an automatic system is doing the complete job.

6. The desired flight path should be defined so that the maneuvers called for are as gradual as the required operation allows. If all maneuvers that are necessary to follow the desired path are well within the performance capabilities of the aircraft, and if navigation and attitude data are of adequate quality, it can be assumed that stable control of flight along the path is possible.

7. The precisions and the data rates of navigational information that are required for stable flight along a given final approach course depend on the shape of the desired flight path, tolerances imposed on deviations from the path, and lags in aircraft response to various movements of controls. The precision and data rates of the system should be adequate for all types of aircraft that will use the system.

8. The volume of airspace within which the necessary data for guidance and control of aircraft are provided must cover all usable final approach paths, as well as some portion of the roll-out paths over the runway surface. The required horizontal limits of coverage by the landing system are determined by two factors, neither of which is solely concerned with the fundamental final approach jobs - horizontal alignment with the runway and control of the rate of descent. These two determining factors are (1) the approach-gate widths that will allow expeditious traffic control procedures to be used when peak traffic density occurs, and (2) the divergence from the runway centerline after landing (during roll-out along a high-speed turn-off path) that must be allowed before control by the surface guidance system becomes effective.

9. Horizontal coverage should extend about 12 degrees on each side of the runway centerline with respect to an angular origin at the stop end of the runway.

10. The ground can be considered as the lower limit of required coverage and elevation though aircraft probably will not fly on glide angles below 1 degree. The upper limit of elevation coverage should be set by the maximum usable glide angle for any type of aircraft. It is estimated that the upper limit of coverage for routine approaches could be about 12 degrees (relative to the touchdown zone). However, the required limit should not be less than 20 degrees of elevation angle in order to provide for service to aircraft using high angles of glide under emergency conditions.

11. Coverage should extend to at least six miles from the touchdown zone of the runway; however, it would be desirable to provide service to much greater distances (perhaps 20 miles), since - when traffic conditions allow such approach paths - some aircraft may use the guidance data throughout a long straight-in approach.

12. The system that provides horizontal and vertical guidance to the aircraft during final approach will depend on the radio transmission of some data between ground base and airborne components of equipment. These transmission channels should be interference free in order to avoid the generation of spurious guidance commands or the distortion of requisite commands.

13. Relatively large inaccuracies can be tolerated during the initial approach if corrections are positive and effective as the final approach begins or as the aircraft proceeds past the outer marker the system must correct positively enough to assure the pilot that only small corrections will be necessary as the aircraft descends below 500 feet.

14. Below 200 feet controlled movements must be kept to a minimum to avoid confusion between whether a large correction is required or the all-weather landing system is starting to malfunction. An occasional missed approach because of poor runway alignment as a result of extreme wind shear would be more acceptable than extreme corrections at low altitudes even though the approach was successful.

15. The system must not only provide adequate guidance from the point of view of both accuracy and response to the entire approach through touchdown but must also provide adequate speed control which directly affects the roll-out and hence the runway length required for operation.

16. The system must provide a means for flareout to assure that the aircraft will touchdown at an optimum rate of descent.

17. The system must provide a means for compensating for any cross-winds influencing aircraft attitude prior to touchdown.

18. A back-up system must be provided which will allow for equally safe and accurate performance or the execution of a missed approach in sufficient time.

19. The primary system must be easily disengaged for override control by the back-up system.

20. All-weather landing systems are important for two reasons other than the landing of a single aircraft. The first is that terminal area traffic will undoubtedly increase in the future and thus higher IFR traffic densities must be accommodated. The second reason is the increasingly wide spectrum of aircraft characteristics that must be accommodated, particularly the different approach speeds involved. Thus one of the requirements for future all-weather landing systems is to allow high sustained landing rates, perhaps two landings per minute on a single runway by aircraft using intermixed approach speeds, say between 60 knots and 240 knots.

3.3.2 Typical Sequence of Landing Functions and Events

A review of the basic requirements for all-weather landing and a review of many of the documents referenced in this report lead to the development of the terminal area flight profile presented in Figure 7 and the typical sequence of landing functions and events presented in Figure 8. Referring to Figure 7, "Landing" as used in this report includes those points and segments of the profile between B and J, i.e., beginning with initial approach and terminating with the completion

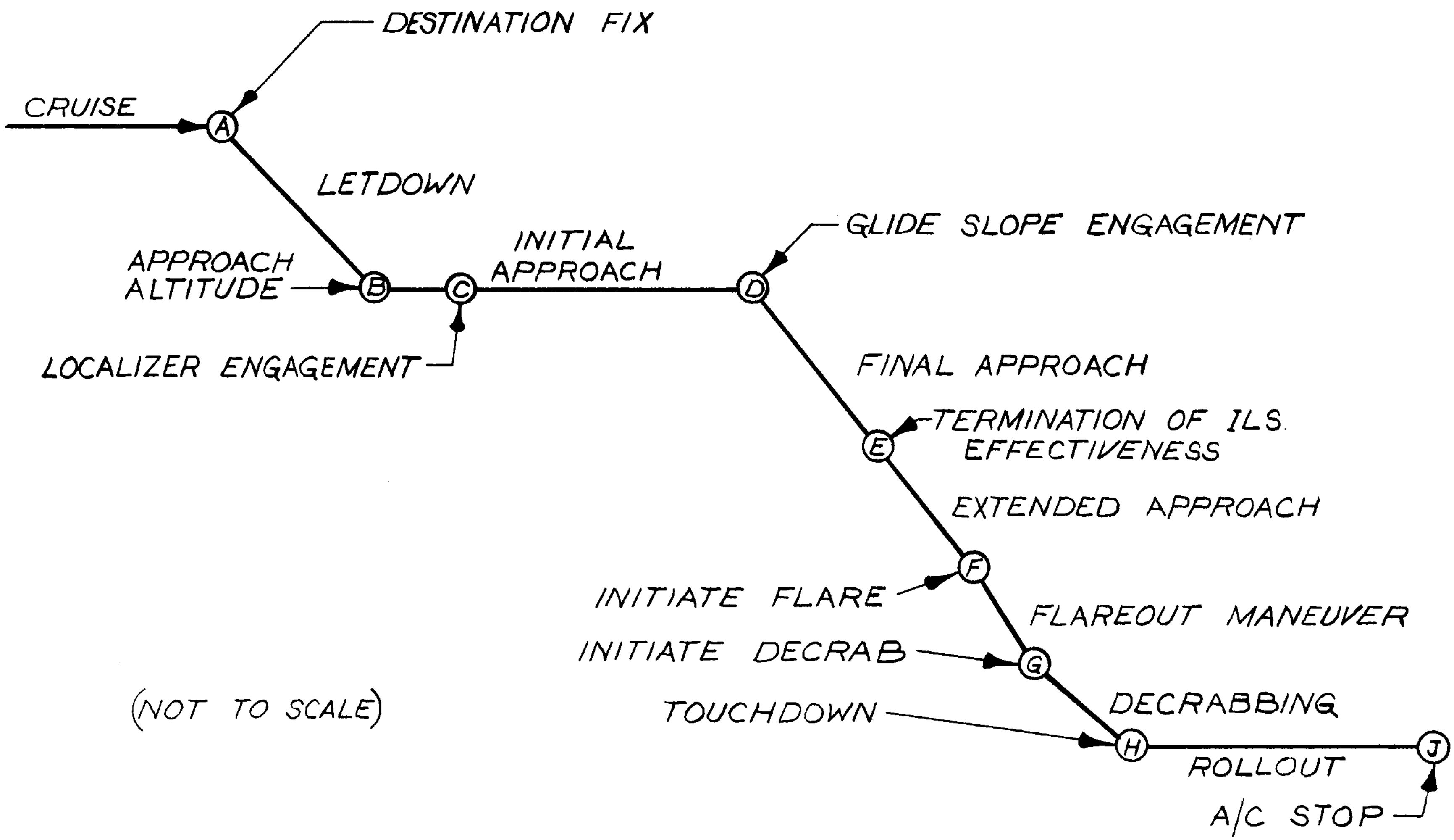


FIG. 7. AIRCRAFT TERMINAL AREA FLIGHT PROFILE

of roll-out. The general segments of landing functions or events is presented in Figure 8. These functions and events are typical of a large turbo jet commercial transport and may of course vary considerably for various types of aircraft or airports.

3.3.3 General Requirements Associated with the Implementation of Landing Functions

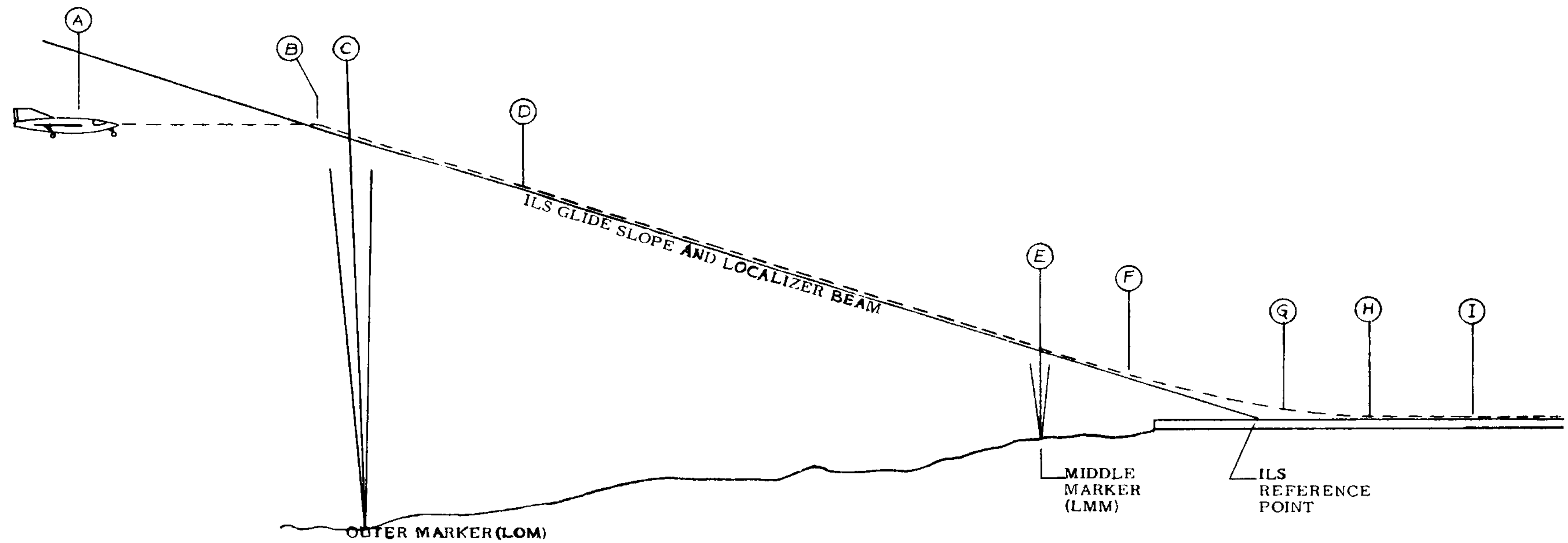
The general requirements for all-weather landing have been analyzed and a list of specific functions (or events) and their requirements and constraints identified. The specific functions (or events) derived are listed below:

1. Acquisition or Initiation
2. Airspeed Control
3. Approach Lateral Guidance
4. Approach Vertical Guidance
5. Flareout
6. Decrab
7. Touchdown
8. Roll-out
9. Go-around

Each of the above functions (or events) is discussed separately in the remainder of this section in terms of its requirements performance. Control parameters and control data are included where appropriate.

3.3.3.1 Acquisition or Initiation

Acquisition or Initiation refers to the method by which the aircraft (and pilot) engage the terminal area approach and landing system during initial approach. Typically an aircraft descends from cruise altitude to an approach altitude and course which is maintained until the approach system is acquired or initiated. The lateral guidance function will



Point or Segment	Event or Function	Reference	Remarks
A	Acquire Lateral Guidance Subsystem	10-25 miles out	Aircraft should be at proper altitude & heading (up to 90° from course direction is desirable)
A	Initiate Approach Airspeed	10-25 miles out	Approach airspeed should be initiated prior to acquiring lateral guidance subsystem
A-B	Maintain Initial Approach Airspeed	V ref + 30 knots	Approach speeds vary with gross weight, V s = stall speed, 1.3 V s = V ref
A-C	Stabilize on lateral flight path	3 miles	Minimum distance allowable for lateral stabilization
A-H	Maintain Lateral Guidance	± 1.5°	Accuracy will actually vary as a function of distance
B	Acquire Vertical Guidance Subsystem	Prior to LOM	Glide path is acquired from below requiring pitch over at intercept
B-D	Stabilize on Vertical Flight Path	> 2m. from LOM	Stabilization should be accomplished within 2 miles of the outer marker
B-F	Maintain Vertical Guidance	± .5°	An essentially constant rate of descent is maintained
B-E	Maintain Final Approach Speed	V ref + 10	Varies with gross weight
D	Aircraft Stabilized on Flight Path	> 2 mi. from LOM	Lateral and Vertical stabilization criteria should be satisfied by this point
E	Initiate Extended Glide Slope Guidance	≈200 feet	ILS Beam may be unstable below 200 feet
F	Initiate Flareout	150 - 50 ft.	A smooth transition from vertical guidance to flareout should occur
F-H	Flareout Maneuver	≈10/ft. sec-2ft/sec	Airspeed gradually diminished to flight Idle
G	Initiate Decrab	≈15 ft.	Side slip technique can eliminate decrab
H	Touchdown	Variable	Touchdown point is variable but ideal point would be in the order of 1200 ft. beyond threshold
H-I	Roll-out	Variable	Roll-out can vary from about 3000 ft. to 12000 ft. depending on conditions

Fig. 8 A Generalized Sequence of Landing Events

usually be initiated first and the vertical guidance function second. Airspeed control for approach and landing will also be initiated during the initial approach segment.

Requirements and Constraints

1. The lateral guidance function should be initiated at least 10 miles out from the touchdown point.

2. The vertical guidance function should be initiated prior to the time the aircraft passes over the outer marker on the final approach.

3. The basic requirement for ILS engagement and intercept is that the aircraft acquire the localizer smoothly and without excessive roll after a turn onto the final approach at anything less than 90 degrees to the inbound heading. If it is then below glide slope, interception of the glide slope should be accomplished without changing altitude. Upon intercepting the glide slope, the aircraft should be precisely controlled along the localizer and glide slope, again without excessive or disturbing roll or pitch control.

3.3.3.2 Air Speed Control

Airspeed control is a method for controlling the thrust and/or drag of an aircraft so as to compensate for airspeed deviations from desired or optimum values. Airspeed control is maintained throughout the landing sequence. For typical landing operations there are three basic airspeed control requirements during approach and landing.

Requirements and Constraints

1. An airspeed must be set up and maintained that is optimum for initial approach and interception of the localizer and glide slope.

2. An optimum speed for final approach is necessary to facilitate the vertical guidance control of the aircraft. Speed control during final approach will facilitate glide slope control by reducing or eliminating the velocity changes and therefore enabling a more stable flight path; speed control will also eliminate possible instabilities due to the necessity of

flying near or below the minimum drag velocity. An airspeed which is too slow has obvious implications and an excessively high airspeed during final approach can result in touchdown too far down the runway and an excessive landing roll.

3. Because there are variable approach speeds due to landing gross weight variations, the aircraft must either touchdown at different airspeeds or reduce its velocity during flare in order to achieve a consistent touchdown airspeed. Any excess airspeed which causes the aircraft to float just prior to touchdown will place it in the "blackhold" before touchdown is accomplished. Further, touching down with excessive airspeed may result in contacting the ground nose wheel first, which is an even greater landing hazard.

3.3.3.3 Approach Lateral Guidance

Approach lateral guidance is a method for controlling the position of an aircraft in a horizontal plane from the point of acquisition during initial approach until touchdown. This control is maintained relative to the extended runway centerline referred to as the localizer path. The basic problem of lateral guidance and control is illustrated pictorially in Figure 9 and discussed in a WADC report (3) as follows:

> "Determination of the horizontal position relative to the runway is inherently a two-dimensional problem, and two elements of navigational data are therefore required. It can be shown that an aircraft's geographical position is definable - among other ways - by its rectangular coordinates (x - y), by its polar coordinates (R - Θ), or by the inter-sections of various types of loci - circular, radial, hyperbolic, etc. The type of coordinate system represented by the directly measured data, and the choice of an origin, are significant factors in determining the complexity and reliability of a given technique.
>
> ". . . in some techniques the position relative to the runway centerline can be treated as though it involved only one dimension - either lateral displacement, y, or angular displacement, Θ - and its

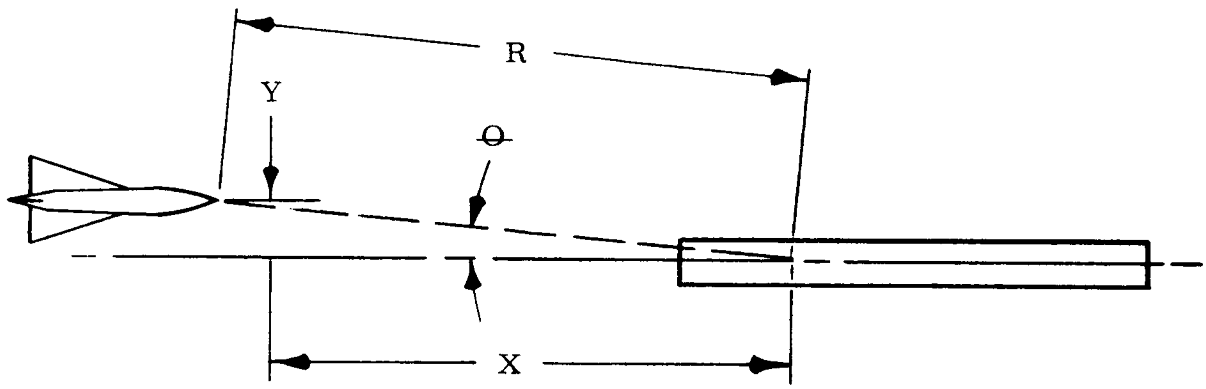


Fig. 9 Lateral Guidance Problem Geometry

variation with respect to time. Although these techniques seem to ignore the need for a second positional coordinate, they actually depend on the determination of distance by dead reckoning, within tolerances that are, fortunately, large."

Requirements and Constraints

1. It has been estimated (3) that the maximum useful horizontal coverage by the landing system is bounded by a sector extending about 12 degrees on each side of the runway centerline, with respect to an angular origin at the stop end of the runway. For one-minute final approaches, the coverage should extend to at least 6 miles from touchdown; coverage to greater distances - perhaps 20 miles - would be useful under conditions of light or homogeneous traffic.

2. The required accuracy of the data defining bank angle and relative heading is further estimated to be essentially the same for future final approach guidance applications as the accuracy afforded by present-day vertical gyros and slaved gyrocompasses. The task of following the proposed horizontal approach courses should, therefore, be no more demanding than is the current ILS procedure.

3. The general estimate for the precision in the measurement of angular displacement from the runway centerline is about $\pm$ 0.1 degree. This estimate is based on an allowable horizontal displacement of $\pm$ 15 feet from the intended flight track at touchdown, subtended from an angular origin 10,000 feet away (beyond the stop end of the runway and on the assumption that control of the approach course will impose an accuracy requirement no more stringent than applied to final displacement).

4. Tolerances imposed on deviations from the desired flight path during final approach might be allowed to vary as a function of time-to-go to touchdown, but it would be more convenient, and probably would be satisfactory, to hold them constant. At actual touchdown, limits are suggested by the dimensions of the runway. The desired flight path during the approach is one of a family of optional paths, and as such is defined

in terms of a direction of flight appropriate to any position within the final approach airspace. The tolerable deviation from this direction of flight depends on the time-to-go, on the allowable rate of turn, and on the aircraft-response lags in achieving a particular rate of turn.

5. Requirements for good localizer control are a positive capture of the beam, smooth control to the beam center, and effective compensation for wind shear effects. The greatest single factor which makes difficult the fulfillment of these requirements is localizer beam noise and bends.

Control Parameters and Data Requirements

There are two basic control parameters for aircraft lateral flight path motion during approach and landing. One is directional motion (rotation above the vertical axis) and the other is rotational motion (rolling moment). These parameters are usually referred to as relative heading and bank angle. Small changes in heading are controlled by rudder displacement and bank is controlled by aileron displacement. Except for small changes effected by rudder control, motion in the directional plane must be considered as a unit, because displacement of the aircraft about either axis induces a moment of sufficient magnitude to cause motion about the other axis (for example, an airplane will not bank without tending to turn, nor turn without tending to bank). Control data requirements and sources have been outlined in a WADC study (3) as follows:

> "It is assumed that an aircraft can be controlled, as necessary, to follow any desired path that is compatible with the performance capabilities of the aircraft. Correlatively, it is assumed that the pilot or autopilot can be relied upon not to sacrifice aerodynamic stability in attempting to follow a given course. To ensure successful approaches despite the disturbances normally experienced, however, the control functions should avoid calling for excessive maneuvers in the process of reducing

navigational error; otherwise, an oscillation about the on-course direction of flight is likely to occur.

"Stable control of the horizontal path requires that some indication be provided of how closely a given change in bank angle corresponds to the potential correction of a given error in a given time. The change in bank angle should be controlled by the magnitude of either the error in track angle (for the current displacement from the centerline) or the error in rate of turn (for the current displacement and track angle) - or by the combined effects of these errors, if both are present. Both bank angle and heading data may be needed for this purpose. (Relative-heading information will also be required for the decrabbing maneuver just before touchdown.)

"The rates of change of aircraft-position data are required for a flight director mode of guidance (such as is provided by the Zero Reader and similar systems), but there is no apparent requirement for attitude-rate (roll-rate) data.

"The data that are needed to define the instantaneous attitude of the airframe (bank angle and relative heading) are obtainable from presently available sources - the vertical gyro and the gyrocompass.

"The data that are needed to define the instantaneous position of the aircraft relative to the runway can be obtained from various sources such as ground radar sets or combinations of ground and airborne equipments similar in function to ILS, VOR, DME, Tacan, Shoran, Radio Web, etc. The ground-based equipment used in any of the indicated techniques must measure or allow air-derived measurements of angles, distance, propagation-time differences, or other coordinates. These data, if air-derived, should be directly measurable in order that a minimum of airborne computing equipment will be needed. If ground-derived, the data should preferably be transmitted to the aircraft in directly usable forms.

"The combinations of horizontal position data that would be most directly usable include either lateral or angular displacement from the runway centerline, and either distance-to-go or time-to-go to touchdown. No practical technique is known for the direct measurement of lateral displacement from the extended runway center - though its computation from ground-radar data, individually for each aircraft, is not difficult. Angular displacement from the runway centerline is directly measurable if ground equipment can be sited on the centerline (beyond the runway itself). The angular data could be ground-derived by radar and transmitted to each aircraft, but this technique offers little if any advantage over one requiring airborne measurement.

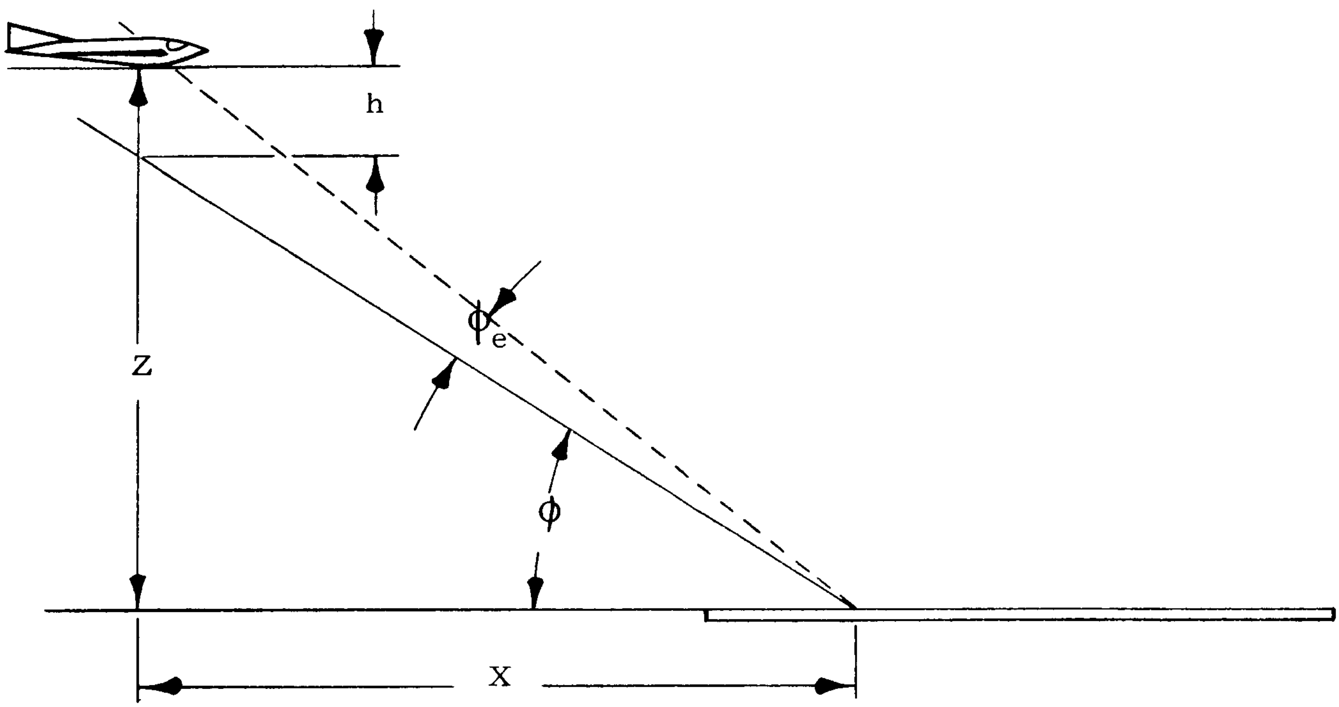
"Distance-to-go data can be obtained either by ground radar or by airborne distance-measuring equipment, and involved only trivial computation if the distance origin (ground equipment) is located on (or nearly on) the projected line of flight. When such siting is allowable, however, its use for angle-measuring ground equipment can obviate the precise measurement of distance...so that the readier availability of distance data from a radar set is not significant. Time-to-go information can be derived by dead reckoning with sufficient precision for use with displacement angle. Elapsed time is measurable within the aircraft, and its equivalent in distance traveled can safely be assumed. The proposed control functions do not require explicit distance data, provided that the starting distance from touchdown is known to be more than sufficient - an easy task for the terminal-area navigational facilities."

3.3.3.4 Approach Vertical Guidance

Approach vertical guidance is a method for controlling the position of an aircraft in a vertical plane from the beginning of final approach (a point equivalent to glide slope engagement) through an extended approach segment to the initiation of flareout. This control is necessary to maintain the aircraft on a desired or optimum straight line vertical flight path referred to as the glide slope.

The problem of vertical guidance and control is illustrated pictorially in Figure 10.

An aircraft which is at present flying at a point vertically displaced from the desired glide angle, as defined by the glide slope, should smoothly



ϕ - Desired Glide Slope
ϕ_e - Glide Angle Error
Z - Altitude
X - Distance
h - Elevation Error

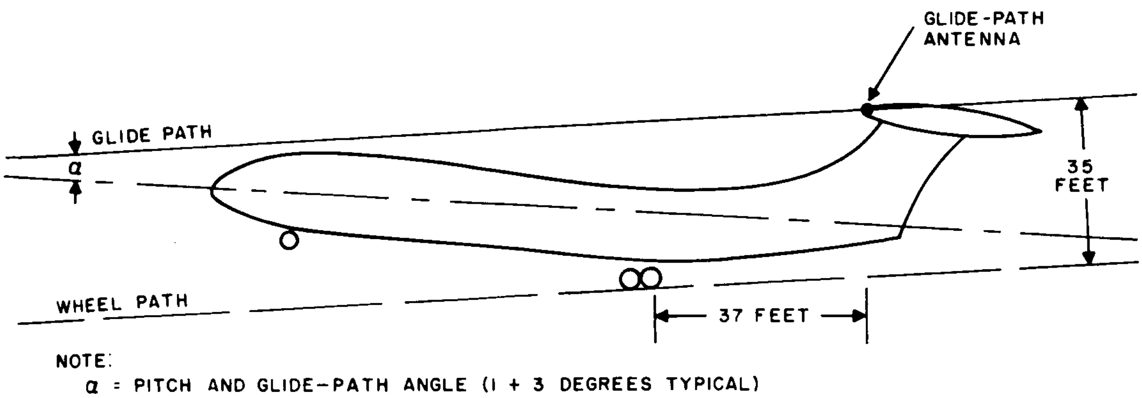
Fig. 10 Vertical Guidance Problem Geometry enter and maintain a flight path coincident with the correct glide path of approach. The source of information regarding the position of the aircraft relative to its desired position is an error signal derived from the vertical guidance subsystem. The error output of the subsystem as indicated by angle "ϕ_e" in Figure 10 is proportional to the angular deviation of the aircraft from the desired glide path line of approach, or may be expressed as a function of vertical displacement "h".

Requirements and Constraints

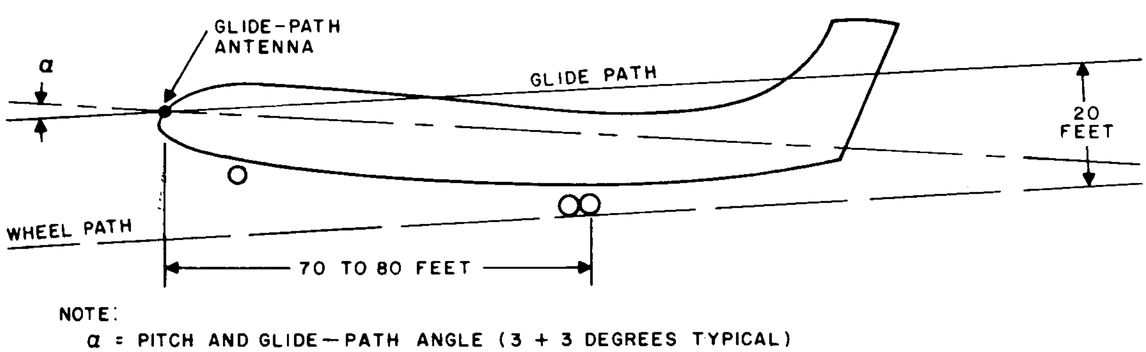
1. The ground can be considered as the lower limit of required coverage in elevation though aircraft will probably not fly at glide angles below 1 degree. The upper limit of elevation coverage should be set by the maximum usable glide angle for any type of aircraft. It is estimated that the upper limit of coverage for routine approaches could be about 12 degrees (relative to the touchdown zone). However, the required limit should not be less than 20 degrees of elevation angle in order to provide for service to aircraft using high angles of glide under emergency conditions.

2. For one minute interval final approaches the coverage should extend to at least 6 miles from touchdown; coverage to greater distances, perhaps 20 miles, would be useful under certain conditions. The required precision in the measurement of angular displacement in the vertical plane has been estimated at ± 0.1 degree. An angular error of ± 0.1 degree is equivalent to a height error of less than 2 feet, subtended from a site that is typically 1,000 feet away. An angular error of ± 0.1 degree should be tolerable during final approach and flareout to touchdown.

3. The vertical guidance technique must account for the position of the antenna point target on the aircraft with respect to the wheel position. Differences in antenna position account for considerable variation in "glide path" to "wheel path" distance as illustrated in Figure 11.



A. TAIL-MOUNTED ANTENNA ON TYPICAL LARGE JET



B. NOSE-MOUNTED ANTENNA ON TYPICAL LARGE JET

Fig. 11 Examples of Distance Between Glide Path and Wheel Path on Approach, Depending on Antenna Location

Control Parameters and Data Requirements

There are two basic control parameters for aircraft vertical flight path motion during approach and landing. One is translational motion (lift force) and the other is rotational motion (pitching moment). In general flaps, boundary layer control, and spoiler surfaces are characterized as lift type control mechanisms; horizontal stabilizer and canard surfaces are moment mechanisms. Though either mechanism is adequate on a short period basis, the pitch control method may induce large changes in velocity resulting in unsatisfactory control. To alleviate this situation tight velocity control is required with possible large variation in thrust required to maintain the velocity.

The manner in which vertical flight path control is effected using lift and pitch moment control is discussed in a recent North American Aviation report (15), portions of which follow:

> "In defining the capabilities of the lift and moment surface controls, consider the air vehicle above the desired glide path (as indicated in Figure 10). To reduce the error, the moment surface control would reduce the angle of attack resulting in a change of normal acceleration in the negative direction (toward the earth). This negative normal acceleration changes the flight path to bring the air vehicle toward the desired glide path; however, an increment of gravity is also produced in the direction to increase the velocity. In addition, the reduction in the angle of attack would decrease the drag due to angle of attack resulting in additional increase in velocity.
>
> "To reduce the glide path error, the lift surface control reduces the lift on the air vehicle causing it to accelerate down, changing the flight path to bring the air vehicle toward the desired glide path. This change in the flight path results in the same additional increment of gravity increasing the velocity as before; however, the increase angle of attack resulting from the loss in lift causes an increase in the air vehicle drag tending to compensate for the gravity effect. Considerable less change in velocity is experienced with the lift surface . . ."

The various types of navigational information that would be suitable for overall glide path control, including flareout, have been identified by Litchford, et al, (18) and are listed in Table 1. Each group represents the necessary and sufficient parameters (except for rates of change) of a hypothetically usable control function. Only directly measurable quantities are included (additional rates of change can be derived, if needed). The list is discussed by its compilers as follows:

> "This list involves six types of directly measurable information. Distance, elevation angle, and azimuth angle define a position in terms of polar coordinates; altitude and distance define a position (in the vertical plane containing the runway centerline) in terms of rectangular coordinates. In addition to the four distinct quantities just mentioned, two rates of change are measurable directly (that is, without first determining the integral quantities): rate of descent, and rate of approach toward the origin (radial velocity). The practicability of direct measurement of these two quantities, with sufficient accuracy for flight path control, may be questioned; however, rate of descent should soon be accurately obtainable, from an inertial sensing device if not from a barometric one; radial velocity might be obtained by use of a Doppler technique more simply (for equivalent accuracy) than by actual distance measurement."

TABLE I

INFORMATION REQUIRED FOR OVER-ALL GLIDE-PATH CONTROL

Data	Origin of Coordinates*	Remarks
1. a. Altitude (z) b. Distance (x)	Virtual touchdown	May compute from range to offset origin.
2. a. Altitude (z) b. Elevation angle (ϕ)	Offset	
3. a. Altitude (z) b. Azimuth angle (γ)	Offset	
4. a. Elevation angle (ϕ) b. Distance (x)	Offset Virtual touchdown	See 1. b.
5. a. Elevation angle (ϕ) b. Azimuth angle (γ)	Offset	
6. a. Elevation angle (ϕ) b. Altitude (z)	Virtual touchdown	Initial glide uses ϕ (or $d\phi/dt$) only. Flare-out uses z (and dz/dt) only.
7. a. Elevation angle (ϕ) b. Rate of descent ($\dot{z}$)	Offset	Derived from vertical acceleration.
8. a. Elevation angle (ϕ) b. Radial velocity ($\dot{R}$)	Offset	Range rate only; DME not needed.
9. a. Elevation angle (ϕ) b. Rate of descent ($\dot{z}$) c. Radial velocity ($\dot{R}$)	Offset Offset	 See 7. b. See 8. b.
10. a. Elevation angle (ϕ) b. Rate of descent ($\dot{z}$) c. Azimuth angle (γ)	Offset Offset	 See 7. b.
11. a. Elevation angle (ϕ) b. Azimuth angle (γ) c. Altitude (z)	Offset Offset	Initial glide uses only ϕ and approximate γ; flare-out uses z (and dz/dt) only.
12. a. Elevation angle (ϕ) b. Elevation angle (ψ)	Offset Offset	Initial glide uses only ϕ, with standby measurement of ψ; distance to switchover is computed by using ϕ and ψ, and distance after switchover is reckoned as a function of time elapsed after switchover. Distance data and ψ are used in computing z and $\dot{z}$ for flare-out guidance.

(Taken from Reference 18)

3.3.3.5 Flareout

Flareout is a maneuver for changing the aircraft attitude and reducing the rate of descent just prior to touchdown in order for the aircraft to have a desirable angle of attack for runway contact with the main landing gear and to touchdown at an optimum rate of descent. Flareout is usually initiated when the aircraft is in the vicinity of the runway threshold and results in a gradual change in attitude and rate of descent until touchdown.

Present concepts for final approach vertical guidance are to control the aircraft along a straight line path which intercepts the runway in a vertical plane and is aligned with the runway in a horizontal plane. The rate of descent of the aircraft is then directly proportional to its approach speed. Current instrument landing system installations include a glide slope beam inclined at an angle of 2.5 to 3 degrees. It is impractical to lower this approach beam any further because of terrain clearance and radiation problems, and in fact with higher performance aircraft it may be desirable to have higher approach angles. Thus the solution to change from a high rate of descent (as much as 60 feet per second for high speed aircraft) to a nominal rate of descent (approximately 2 feet per second) at touchdown is to flare the last segment of the vertical flight path. This is illustrated in Figure 12.

The actual shape of the flared path is somewhat arbitrary since there are literally an infinite number of paths which could conceivably be used in changing the rate of descent, pitch attitude, and air speed from the initial values existing during final approach to the values specified for touchdown.

Requirements and Constraints

1. Flareout must be initiated and controlled to meet the touchdown criteria appropriate for the particular aircraft.

2. Transition from vertical guidance to the flareout maneuver must be smooth with no abrupt change in flight path.

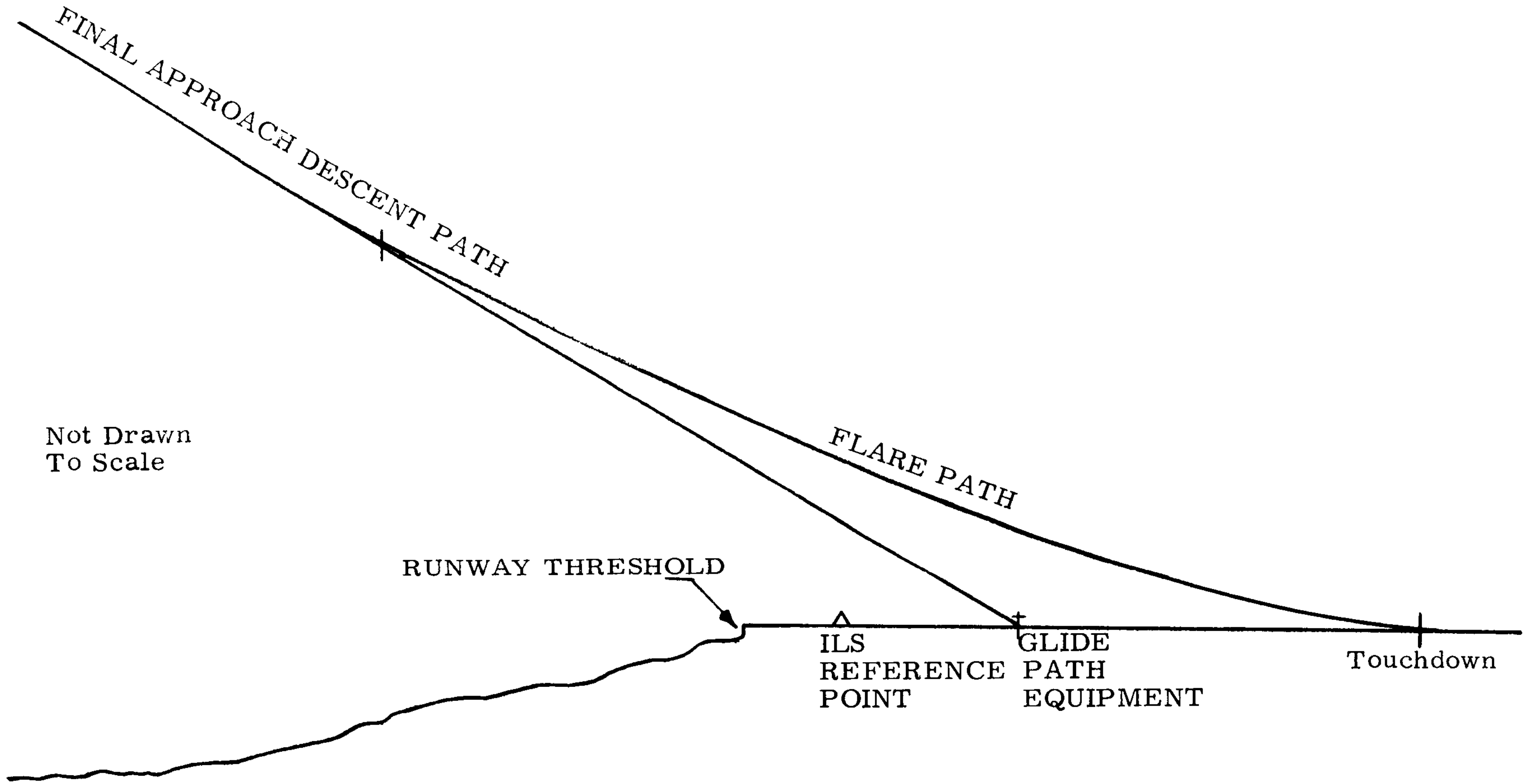


Fig. 12 General Flareout Geometry

3. The flare path itself should be smooth with sharp bends and a minimum of curvature.

4. Curvature of the path should have its maximum value early in the flareout. At this point the airspeed is maximum with respect to the flare and at this time there is greater margin for path errors.

5. The choice of flared path and control technique must consider the possibilities of displacements due to wind gusts or other disturbances.

6. If a radio technique is pursued the following requirement has been identified by an Airborne Instruments Laboratory representative (19):

> "The angle required to cover this operation is quite wide including some very low limits. The lowest angle is determined by taking into account the height of the aircraft antenna; its desired final flare angle upon intercepting the runway, and a margin of safety so that an updraft will not "float" the aircraft out of the coverage of the system. For nominal values, assume a 20-foot aircraft antenna, a 1/2-degree angle (which is a rate of descent of 2 ft/sec at a speed of 120 knots) for contact, and a 2000-foot margin; it is evident that the coordinates must reach a low elevation angle of 1/2 degree (assuming the radiation source is 5 feet from the ground). See Figure [13] ."

3.3.3.6 Decrab

The basic requirement of the decrab function is to remove any angular difference between the heading of the aircraft along its longitudinal axis and the runway centerline at touchdown. In order to insure a safe landing the ground track of the aircraft and the longitudinal axis of the aircraft should be coincident along the direction of the runway centerline at touchdown. The decrab problem is illustrated in Figure 14.

During final approach when the aircraft is under control of the lateral guidance subsystem the proper ground track along the extended runway centerline may be maintained by crabbing the plane into the wind; that is, by heading the plane at the proper angle relative to the runway centerline to cancel the lateral drift caused by cross-winds. If this crab

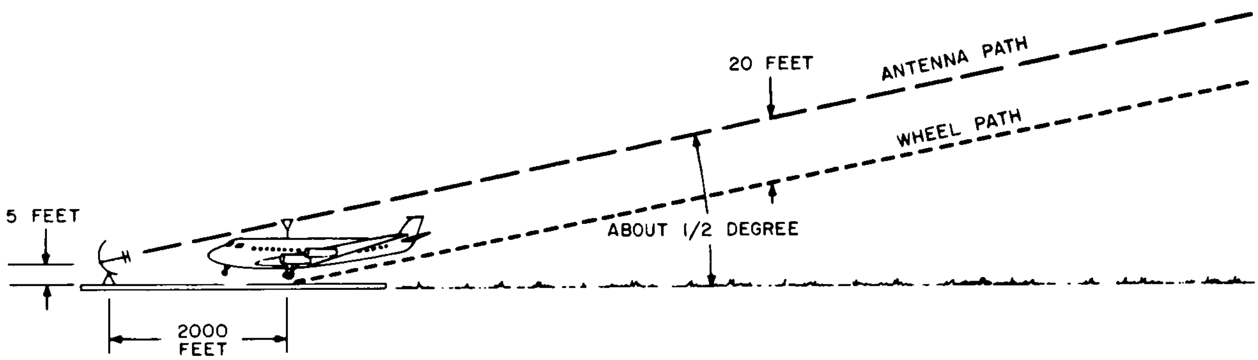


Fig. 13 Minimum Flareout Angle Considerations

(Taken from Reference 19)

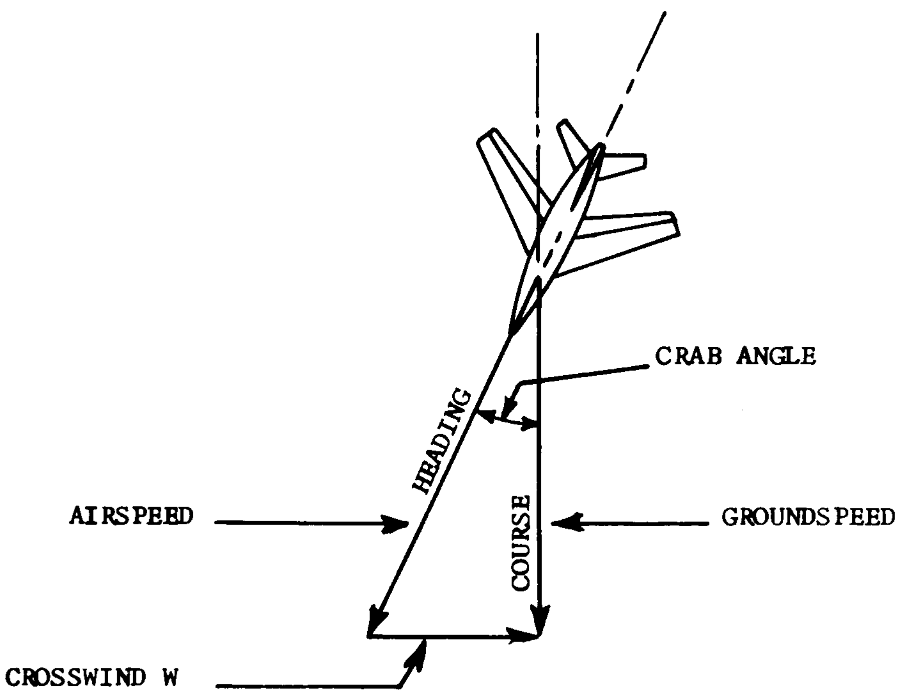


Fig. 14 The Decrab Problem Geometry

(Taken from Reference 26)

angle was held all the way to the runway touchdown sudden large side loads would be produced on the landing gear at the moment of impact which could permanently damage the landing gear and aircraft (this is assuming that the aircraft does not have castered landing gear). Further, the problem of initial roll-out guidance is amplified as the angle formed by the longitudinal axis of the aircraft and the runway centerline at touchdown increases.

There are two general approaches to alleviate the crab angle problem. The first is the use of a flat turn decrab maneuver to remove the crab angle just before touchdown; the second is the use of a wing-down condition with adverse rudder to compensate for the cross-wind. In this latter case no heading correction but a simple roll maneuver to nearly level is required before touchdown. When decrabbing is used the time or height at which the decrab maneuver is initiated is critical. If the decrab maneuver is executed or initiated prematurely the aircraft lateral velocity will be higher than optimum, if decrab is executed too late less that optimum crab will be removed. In either case undesirable side loads will be imposed upon the landing gear and initial roll-out guidance problem is more severe. Decrab is usually initiated at some predetermined altitude or as a function of time to go to touchdown if computing equipment is part of the flight control system.

3.3.3.7 Touchdown

Touchdown of the aircraft on the runway must be accomplished within the limits of several criteria in order to insure a safe landing. While the limits of these criteria will, of course, vary from aircraft to aircraft, the basic criteria to be satisfied for safe touchdown are as follows:

1. The rate of descent at touchdown must be below the allowable maximum for the landing gear. The most generally accepted nominal rate of descent at touchdown is 2 feet per second with a desirable standard deviation of about 0.5 feet per second.

2. The touchdown aim point and dispersions from that aim point in the longitudinal and lateral direction must be specifically determined for each installation and type of guidance and control system. In general the touchdown aim point can be considered to be 1000 feet behind the ILS reference point. Longitudinal dispersions around the aim point should have a standard deviation not to exceed 250 feet. Lateral dispersions around the aim point should have a standard deviation not to exceed 5 feet.

3. The aircraft heading relative to the runway centerline must define an angle as close as possible to zero degrees at touchdown to minimize stress on the landing gear and to minimize the problem of initial roll-out guidance. The maximum allowable angle will depend upon the characteristics of the various aircraft, but it is generally in the order of 4 to 5 degrees. This criterion can also be considered as a maximum allowable axial component of velocity of the main landing gear wheels relative to the runway; again this depends upon the particular aircraft involved, but a general maximum value of 3 feet per second lateral velocity is reasonable.

4. The pitch attitude of the aircraft at touchdown must be between allowable limits to avoid damage from improper ground contact or stall of the aircraft. The optimum pitch attitude will, of course, also depend upon the particular aircraft, but in general touchdown should be made with enough positive pitch attitude to prevent the nose wheel from striking before the main gear touches down, and pitch attitude must be negative enough that the tail of the aircraft does not scrape the runway or the aircraft does not get into a stall condition.

5. Airspeed should be controlled to a nominal value for the particular aircraft at touchdown. Generally speaking this is somewhere between 120 to 140 percent of stall speed for most airplanes. In actual speed values this may vary from 60 knots to 230 knots. Assuming that the rate of descent at touchdown is a fixed value the requirement for pitch attitude establishes a maximum landing air speed that can be used. Since air speed, angle of attack, pitch attitude, and rate of descent are dependent upon each other the minimum air speed that can be tolerated

may be established by either the stalling angle of attack or by the requirement that the pitch attitude be kept low enough to prevent scraping the aircraft tail.

6. Roll attitude must be minimized immediately prior to touchdown. Large roll attitudes at touchdown can damage the plane by causing an outboard engine or a wing tip to scrape the runway. In addition there may be passenger discomfort due to the rocking motion of the plane at touchdown as the plane rights itself. The limits of roll attitude again can depend somewhat on the aircraft, but as a general rule a maximum value of 5 degrees can be used.

3.3.3.8 Roll-Out

The basic requirement for the roll-out function is to maintain directional guidance and decelerate the aircraft down the runway until it comes to a complete stop or to a turn-off into a taxiway which can be safety executed. Runway guidance is initially maintained with rudder (and possibly the ailerons) until the nose wheel makes contact with the runway and forward speed has been reduced. At this time runway guidance is controlled through nose wheel steering. Deceleration during roll-out may be accomplished with wheel braking, thrust reversing, and extending speed brakes or spoilers. It may also be desirable to deflect the ailerons to counter the tendency of the cross-wind to roll the airplane over during roll-out.

3.3.3.9 Go-Around

The requirements for go-around have been fairly well established for landings accomplished under contact conditions, but have not clearly been defined for landings to be accomplished under zero-zero conditions. The Radio Technical Commission for Aeronautics in a report prepared by Special Committee 79 (26), references some operational concepts originally prepared by RTCA Special Committee 18, which concerned go-around. An excerpt of this concept follows:

> "In the conduct of instrument operations under low visilibity conditions, it is expected that a pilot will make his final approach

by the use of Automatic Path Flight from the Outer Marker to a height of 100 feet above the elevation of the airport runway. If, at this point, visual guidance is established, the Autopilot will be disconnected, and the actual touchdown made manually by visual reference to the approach and runway lights. If visual guidance is not established at the 100-foot altitude point, missed approach procedures will be followed. On a normal $2\text{-}1/2^{o}$ Glide Slope, the aircraft will reach a point approximately 100 feet above the elevation of the runway at a distance of about 1000 feet from the approach end of the runway. This point has been designated as the "Decision Gate", since it is here that a pilot must make the decision either to continue the approach to a landing or to execute a missed approach procedure."

Execution of a missed approach procedure constitutes a go-around. While this maneuver is not ordinarily considered to be a high probability event, the potential requirement exists on any approach, since management of the approach by any control system is subject to error and equipment malfunction.

The principal control requirements in the execution of a go-around maneuver are in the timing and effectiveness of changes in the vertical flight path necessary to avoid contact with the ground or runway and the management of air speed. A go-around can be a more severe maneuver than takeoff in that the aircraft could be starting from a landing configuration with approach or landing power and from a negative flight path angle. Trim changes occur during the clean-up and acceleration to climb out speed and changes in aircraft configuration entail attitude changes.

Requirements for a safely executed go-around maneuver will vary with such factors as aircraft type and landing gross weight, surface wind conditions, and approach flight path angle and speed. The most extreme requirements, and they have been met under certain conditions, derive from the necessity for executing a go-around from a position wherein the aircraft is in a full landing configuration and only a few feet above the runway or where it has actually contacted the runway.

4. GENERAL FLIGHT CONTROL TECHNIQUES

In this section, an overview is presented of flight control techniques currently employed or being considered in research and development programs for application to commercial transport approach and landing operations.

Flight control may be construed as a recurring sequence of events directed toward the achievement of specific aircraft positioning and rate of movement control objectives. The principal events which define this sequence are the acquisition of information pertinent to the ongoing flight situation, the determination of control actions required to establish and maintain a desired or required flight path and/or rate of movement, and the execution of control actions. By considering alternative means of implementing this control sequence, a number of different flight control techniques can be distinguished. Differences in flight control techniques can be expected to have important implications for the pilot's role and performance requirements and thus represent a potential source of acceptance problems.

Generalized flight control sequences can be distinguished by reference to Figure 15. In terms of imput/output bounderies, flight control is represented as the processing of energy inputs from the flight environment into the aircraft control actions appropriate to the achievement of specified flight control objectives. In the present study, these objectives would correspond to the general performance requirements discussed in Section 3. 3 for the functions occurring in the landing sequence. Control actions are the control surface displacements, throttle movements, thrust/lift control device (e. g. , spoilers, flaps, thrust reversers, speed brakes, etc.) movements, etc. , required to control the aircraft attitude and both vertical and horizontal movement. The blocks and arrows between the input/output boundaries indicate the alternative input processing sequences; different flight control techniques can be distinguished by tracing different paths.

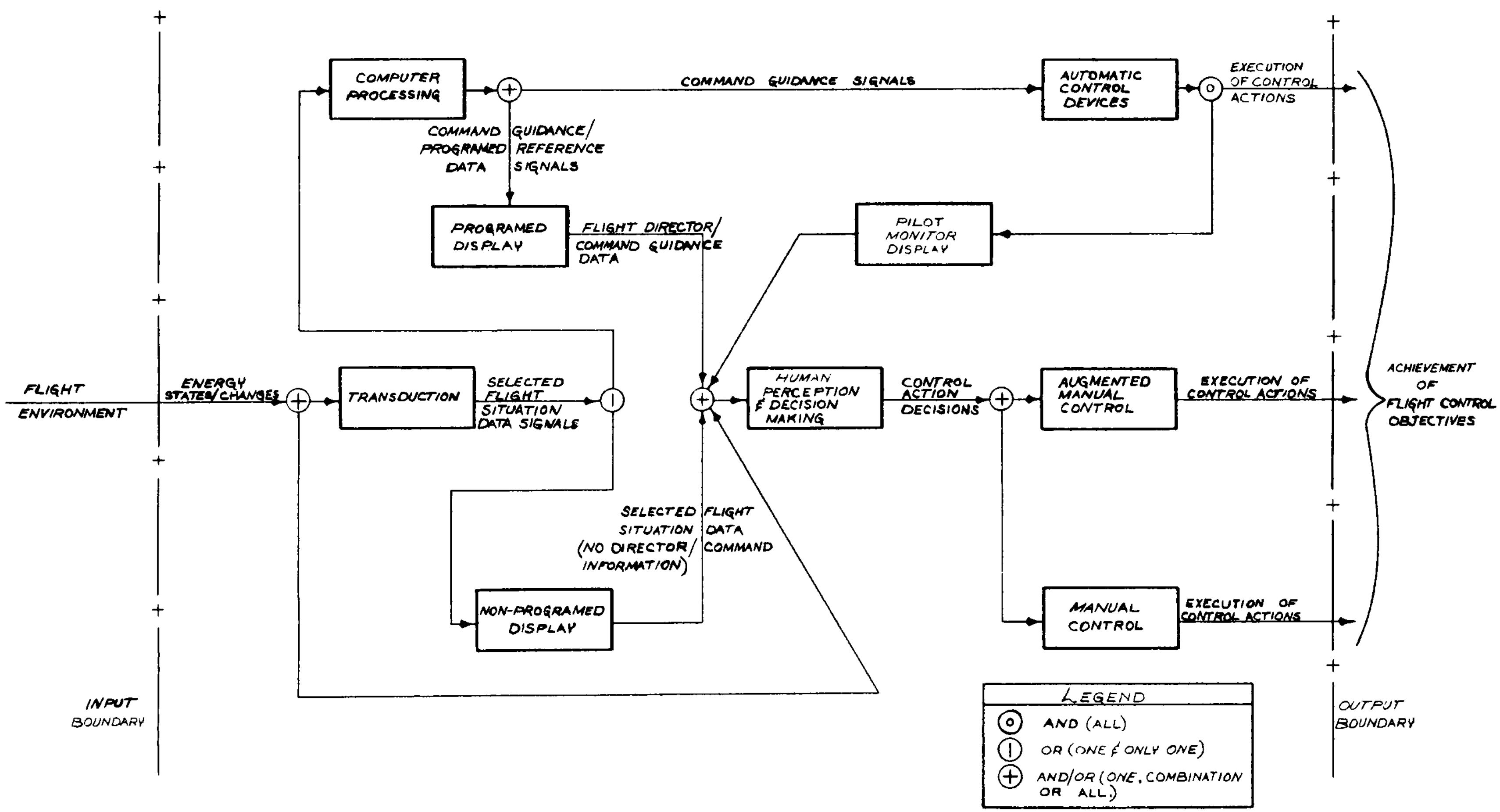


Fig. 15 A Generalized Representation of Alternative and Integrated Flight Control Techniques

For convenience, three clearly distinguished flight control techniques will be discussed: (1) contact flying, (2) flying by instrument reference, and (3) automatic flight control. As indicated in Figure 15, however, these techniques can be combined in a number of ways to achieve a given flight control objective. Furthermore, automatic control techniques may be applied to portions of the flight control problem, as in the split-axis technique (24). In the following sections, each of the three basic techniques is briefly described and their application to the implementation of a landing sequence is illustrated.

4.1 CONTACT FLYING

Contact flying is generally characterized as flight control by visual reference to extra-cockpit phenomena and is so regarded in this report. In a more general sense, however, a flight control technique may be regarded as contact flying whenever important guidance or flight situation information is obtained by a human pilot in direct perceptual contact with the flight environment. This extension provides for the acquisition of information through other sense modalities, although the visual system is clearly the predominant channel. For example, in an earlier era of aviation experience, critical flight control information was obtained by alterations in sound patterns produced by vibrating structural members during certain maneuvers. The point is made not to argue, at this time, that useful flight control information can be obtained in this manner in contemporary and near-future aircraft but to leave open this possibility in any further consideration of flight control problems.

A more important point is that the characterization of a flight control technique as contact flying does not necessarily imply the manual execution of control actions. Thus, although the image of contact flight generally calls for the manipulation of flight controls by the pilot, it would be appropriate to consider certain flight control situations as contact flying even where an autopilot was engaged and some sort of automatic airspeed control device was in operation. For example, a landing might be executed using an ILS-autopilot coupler technique under clear visibility conditions. If the pilot monitored and evaluated the approach principally through extra-cockpit visual reference, this flight control technique could be properly identified as contact flying. The distinguishing characteristic, then, is that information of critical importance in determining control action requirements is obtained by a pilot in direct perceptual contact with the flight environment rather than with representations of the flight situation provided by aircraft displays. In this sense, contact flying may be regarded as a flight control technique that can be applied in any flight situation to the extent that perceptual contact with extra-cockpit phenomena is possible.

Contact flight techniques can be employed in the landing sequence after the airport or ground reference points at known positions relative to the airport are visually acquired by the pilot. It is understood that available navigational aids and instrument reference techniques, rather than contact flight techniques, are commonly employed even under VFR conditions for flight path control in terminal areas. However, in order to illustrate the techniques under consideration, an approach and landing executed primarily by visual reference will be briefly outlined.

The basic flight control objective on the initial approach is to establish and hold a ground track prescribed by local air traffic control procedures. To accomplish this by visual reference the pilot utilizes directional cues provided by known terrain features in the airport surrounds. The effects of wind on the aircraft's ground track are continuously compensated for by adjusting the alignment of the aircraft with these reference points. As the aircraft approaches the entry point for the final approach, the runway and desired touchdown point on the runway, the so-called X-point, become the principal ground reference system and the aircraft is maneuvered to establish a track aligned with the centerline of the runway. It should be noted that aircraft speed and altitude are adjusted throughout this initial approach in order to arrive at the final approach entry point at the altitude specified by local control procedures and at an airspeed appropriate to the landing gross weight and performance characteristics of the airplane. However, this vertical flight path control objective is achieved primarily by instrument reference and, while it cannot be separated from the horizontal flight control problem, it should not be characterized as a contact technique.

Final approach control is illustrated by the following excerpt from the Boeing 707 Operations Manual (4):

> "The recommended control technique on an approach to a landing is similar to the techniques used on an ILS approach. The pilot should mentally picture the specific flight path he will follow from the point of beginning the approach descent to the point of touchdown. He then flies the airplane to maintain this normal approach flight path with a smooth, nearly constant rate of descent while controlling the airplane with the elevator to arrive at the desired flare point. The airspeed is controlled with thrust and/or drag. The airplane will then arrive at the flare point with the desired airspeed and on glidepath."

This final approach control technique may be generalized as follows. Flight path control is accomplished by maneuvering the aircraft so that its movement toward the desired landing point conforms to a previously acquired "perceptual expectancy," i.e., a familiarity with how the extra-cockpit phenomenal field should "look" approaching the touchdown point on a "correct" glidepath at an appropriate speed and rate of descent. Such critical information as airspeed and rate of descent is obtained, of course, by time-shared instrument reference. However, the so called streamer or expansion patterns studied by Gibson, Calvert and others (14) represent important sources of rate of approach and acceleration (or rate of change of rate of approach) information and become the primary source of guidance for flareout and touchdown control.

The most critical application of contact flight techniques occurs in the landing maneuver, which is defined, for convenience, as beginning at that point on the final approach at which the pilot decides (or is otherwise committed) to land, the so called "decision gate," and ending at that point on the roll-out where flight control surfaces are no longer effective. Assuming that available extra-cockpit perceptual inputs and pertinent instrument readouts have led to a decision to proceed to touchdown, the flight control task now becomes primarily one of smoothly decreasing the rate of approach to the touchdown point to a nominal 2 feet per second and establishing the final aircraft alignment and attitude required for a safe touchdown at a prescribed location on the runway. The pilot's perceptual task during the execution of this critical maneuver under contact conditions has been subjected to a number of analyses (21, 14, 25). In general, these studies outline the complexities involved in utilizing cues provided by the apparent expansion pattern of the runway and its immediate surrounds in the critical tasks of establishing final aircraft alignment and controlling rate of closure. Apparent aircraft movements must be detected, compared with the perceptual expectancies which define a "correct" landing situation, and continuously adjusted to conform to these expectancies. Havron (14) has candidly reported that although pilots — and birds — utilize such cues with some precision and a great deal of confidence and reliability, laboratory studies of their perceptual capabilities do not yet tell us how they are able to do so. After the wheels are on the ground, the control problem reverts to the relatively familiar and "more natural" one of maintaining directional control in only one plane, the horizontal plane coincident with the earth's surface.

4.2 FLYING BY INSTRUMENT REFERENCE

Flight control techniques in this category are distinguished by the role of displays, i.e., representations of selected aspects of the flight environment, in determining the timing and execution of control actions. The pilot remains in the primary control loop, as in contact flying, but he is no longer in direct perceptual contact with the flight environment and is now dependent upon sensor equipment and various input processing and display systems for primary flight control information. Considerable operational experience has accumulated in flying by instrument reference and research and development work in support of improved display techniques and extending instrument flight control capabilities has been in progress for many years. No attempt will be made here to cover the many operational problems and specific display and instrument flight control techniques associated with flying by instrument reference. Instead, a brief review of display problems and concepts pertinent to instrument low approach and landing is presented in order to illustrate their effect on the pilot's role in the flight control situation.

The basic display problem is defined by questions which can be resolved into considerations of referents (i.e., which objects, events, conditions, etc., in the flight environment should be represented?), types of representation (e.g., symbolic vs. pictorial, qualitative vs. quantitative, etc.), and representation characteristics (i.e., accuracy, timeliness, reliability, etc.). One would expect to find substantial agreement in respect to information requirements and, perhaps, considerable disagreement regarding the best means for its acquisition and display. But the question of information requirements is inextricably tied up with questions regarding the pilot's role and the allocation of functions in a landing system. As a result, a number of display concepts have evolved and, although there is some overlap in the flight control problems provided for, there are significant differences in corresponding pilot performance requirements. The principal differences center around the level of abstraction from environmental inputs, the extent of pre-display processing of inputs (i.e., correlating, integrating, categorizing, etc.), the presence or absence of directive or command information, and the degree of "naturalness" or correspondence to extra-cockpit phenomena as they appear under contact conditions. Display/instrument flight control techniques categorized to reflect these basic differences are discussed below.

4.2.1 Conventional Instrument Approach and Landing

For discussion purposes, conventional instrumentation for low approach and landing will be understood to consist of the "basic flight control panel," comprised of more or less standardized readouts of airspeed, mach number, altitude, vertical speed, and turn-and-bank indication, and some type of integrated flight system, such as the Collins FD-105 or Sperry Z-4 systems, providing a combination of aircraft attitude, ILS glide slope deviation, computed steering commands, aircraft heading, and aircraft position relative to an ILS, VOR or selected course. Flight control techniques entailing reference to conventional instrumentation have been exhaustively documented and have been used with confidence in routine operational flying for many years. The advantages of reliability, standardization, and optimum redundancy in coverage of basic flight control information (providing for partial panel control) are frequently cited.

The principal limitation in this display system is that both "Joe"* and his more proficient colleagues experience considerable difficulty in attempting to synthesize the readouts of several different indicators, each one representing a separate aspect of the basic flight situation, into a relatively clear "picture" of how the approach is progressing and the control actions required to keep everything within acceptable limits. The amount of effort involved and the demands of instrument cross-checking on pilot attention understandably led to the development of such commonly employed techniques as that of having one pilot direct his attention outside the aircraft while the other flies the approach by instrument reference. This technique provides for the acquisition of external visual cues as soon as they are available and facilitates the transition to contact flight control techniques for a final evaluation of the approach and execution of the landing maneuver. Some improvement in information display over earlier "basic six" flight control panels is reflected in the conventional integrated display system, but these improvements appear to be more on the order of collecting certain related information items together in a combined conventional display rather than providing an integrated representation of the flight situation.

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*"Joe" is a mythical character created by the IATA Flight Technical Group to represent the pilot with the lowest passing grade on an instrument check.

Flight control by reference to conventional instrumentation, then, is still largely a matter of the pilot putting together the critical elements of the flight situation based on a set of digital, needle and dial, and semi-pictorial readouts of displacement and rate information, and continuously comparing actual and desired vertical and horizontal flight paths in order to derive control action requirements. Some command and/or steering information is computed and made available, of course, but in view of the limited operational experience with flight director/command type displays and the special problems they introduce, corresponding flight control techniques are discussed below in a separate subsection. In broad outline, an approach and landing by reference to conventional instrumentation entails the following flight control problems:

1. ILS localizer interception and alignment - prior to accomplishing this control objective, the aircraft is assumed to be descending inbound from its last holding fix to intercept the localizer at the initial approach altitude and at an angle appropriate to the distance of the intercept point from the runway. Initial approach altitude and airspeed are established and maintained by reference to separate instruments on the basic panel. An appropriate localizer intercept heading is established and the turn-on to the localizer is accomplished by reference to the "plan view" course indicator which provides a semi-pictorial display of aircraft position relative to the localizer course and a conventional magnetic heading indication.

2. Stabilization on the localizer course and interception of the glide slope - the basic control problem here is to smooth out the aircraft's alignment with the localizer until corrections on the order of 2^{o} are enough to maintain a localizer on-course indication and to effect a smooth transition from level flight at initial approach altitude to a final approach attitude when the glide path beam is intercepted. Cross reference from the ILS displacement indicators and attitude display to airspeed and vertical speed is required in order to anticipate the final approach entry and to establish an appropriate final approach speed and rate of descent.

3. Stabilization on course, on glide path, and on airspeed and approach to minimum altitude - the accomplishment of this flight objective entails a coordinated manipulation of thrust controls, drag devices (i. e., spoilers, speed brakes, flaps), and flight controls in order to maintain an approach speed and rate of descent appropriate for landing gross weight and local conditions and to keep the aircraft positioned on course and on the glide path with minimum heading and pitch attitude corrections. Principal instrument reference is to the attitude display, localizer course and glide path deviation indicators, altimeter, and rate of descent indicator. When the runway or approach lights are acquired visually, flight by instrument reference is abandoned and a transition to contact flight techniques is effected to accomplish the final approach evaluation and landing.

4. 2. 2 Advanced Display Concepts for Instrument Approach and Landing

The current acceleration of efforts to produce an operationally acceptable all weather landing system has led to an intensification of long standing projects concerned with the development of aircraft instrumentation and display systems. Pilot information requirements during low approach and landing have been extensively analyzed and re-analyzed in support of both specific and general or long range display system design studies. At least two fundamentally different but seldom clearly distinguished concepts regarding the pilot's role in projected reduced minima landing systems appear to underly much of the thinking in this area. One view is reflected in pilot performance models derived from control system theory wherein pilot behavior is described in terms of adjusting gain, lead, and lag in order to close attitude loops in much the same way that autopilot functions are described. When pilot displays are considered, this orientation leads to the specification of programmed command type displays which tell the pilot what he must do, e. g., rate of turn, bank angle, and pitch commands are computed in a manner similar to that employed for the autopilot and displayed, and the pilot's basic task is to continuously null this command readout. A contrasting orientation emphasizes the necessity for pilot judgment and decision making, both in assessing the ongoing flight situation and determining the appropriate control actions. This view underlies the specification of non-programmed situation displays, perhaps incorporating predictive elements and/or computed reference data, which require the pilot to perceive the control action requirements and decide what to do about them.

As indicated earlier, the issue is not so clearly drawn as the foregoing statements would suggest and most proposed display techniques incorporate both command readout and situation depiction features, but the relative strength of the two orientations can be distinguished in display techniques currently under consideration. Flight control techniques implicit in these display concepts are briefly outlined and exemplified below as flight director/command control and approach and landing by non-programmed instrument reference.

4.2.2.1 Flight Director/Command Control

This flight control technique is distinguished by the display of flight path and/or airspeed error and a pilot control task which consists, essentially, of tracking a desired flight path, aircraft attitude, or airspeed marker. The technique is readily exemplified in an approach by reference to computed steering command information provided in operational flight director systems. For example, the Collins FD-105 Approach Horizon display unit provides computed lateral guidance information in the form of a straight, vertical pointer pivoted at the bottom of a conventional attitude reference instrument. Steering pointer deflections constitute bank commands indicating the direction of a correction in lateral flight path required to acquire and hold a preselected localizer course. It is important to note that when the steering pointer is centered the airplane is on the selected course or it is making the correct maneuver to obtain the selected course. The pilot's lateral flight path control task, then, is simply to keep the steering pointer centered.

Additional command information is available on a number of flight directors under consideration and the flight control task can be seen as a set of concurrent tracking activities. For example, in the director mode of a windshield display system developed by Sperry (20) flight path and air speed error are provided by a computer generated positioning of a flight path marker and a set of short bars. The flight path marker, or director sight, symbol looks like this:

In the director mode, this marker is positioned relative to an aiming point on another symbol representing the runway and the pilot's task is to bring the dot between the wings into coincidence with a little cross representing the runway aiming point. Quickening features are incorporated in the display response so that the runway aiming point is "captured" as soon as an appropriate control action is initiated, e.g., rolling into a descending turn to the right when the director sight is positioned above and to the left of the aiming point. The pilot's basic task in achieving flight path control, again, is to keep the director sight on the "target" at all times. When this is accomplished, the aircraft makes a smooth, stable, asymptotic approach to the programmed flight path and then descends toward the aiming point at the programmed flight angle.

Airspeed error is indicated by movement of the short heavy bar relative to the "left wing" of the flight path marker, e.g., when the airspeed is too high, the heavy bar is above the wing. The thin bars represent high and low speed limits. Thrust, drag and/or pitch attitude is adjusted to keep the instantaneous airspeed indicator (heavy bar) within these limits.

Flight directors may be expected to vary in complexity and performance, depending upon whether or not they include such factors as crosswind compensation, corrections for aircraft speed, weight and configuration changes, and the degree of computation for stability included. Furthermore, considerable variation in the display symbology, location, and dynamic characteristics can be expected. But the basic concept remains one of telling the pilot both what is wrong and what to do about it in order to achieve pre-selected flight control objectives, in terms of either roll and pitch commands or displays responsive to changes in control forces or movements.

4.2.2.2 Approach and Landing by Reference to Non-Programmed Situation Displays

The concept underlying the display technique considered here has been concisely stated by representatives of NASA's Ames Research Center who are its principal supporters (underlining added):

> "Ames has undertaken a study of the zero-zero landing problem which is intended to fulfill two special requirements; first, to provide a display with which the pilot can land the airplane, making the same judgments, coming to the same conclusions, and applying the same control techniques that he does during visual landings; and second, to install the sensing and the display-generating equipment on board the airplane . . . . Further, a display which allows the pilot to land the airplane as he does under visual conditions <u>need contain no director or command information, and therefore the equipment to compute such information would not be needed</u> . . . [the pilot] should be able to cope with adversities, such as gusts, cross-winds, and bounces. This implies that he have also the extra information according to which he plans to waveoff should the landing deteriorate . . . He must be able to use the display in conjunction with VFR landings, and in that way develop confidence in the system . . . . Also, the display must minimize - to zero if possible - ambiguity or discord during transition from IFR to VFR under not quite zero-zero conditions."(7)

In general, the orientation reflected in the foregoing quote places relatively greater emphasis on the pilot's role in assessing the moment to moment flight situation and in the determination of what the aircraft should do. The implied flight control technique can be briefly illustrated, in part, by reference to an approach and landing as it might be executed using the Sperry windshield projection display in its non-programmed mode. Critical elements of the flight environment are projected in the pilots forward field of vision and collimated to appear at infinity. In the flight path mode the projection consists of a horizon line with a track or heading reference, an inverted "T" symbol defining the centerline and approach end of the runway, and a flight path marker representing direction of flight and aircraft attitude relative to the runway or horizon line are provided. In use, the horizon line and runway symbol are expected to coincide with the outline of these features of the actual flight environment, i. e. , the runway symbol changes in size, shape, and perspective as the aircraft approaches and maneuvers relative to the runway and the horizon line is, of course, continuously aligned with the actual horizon at low altitudes.

Presumably, such projected synbolic displays of selected ground features and aircraft orientation and direction of movement cues allow the pilot to assess the basic flight situation and apply the same skills to maneuvering the aircraft by reference to them as he employes under contact conditions. Indeed, both the Sperry display and a similar technique developed at the Aeronautical Research Laboratories were initially designed to provide for greater precision in flying by visual reference. Throughout the approach, flight path control would be maintained by positioning the flight path marker relative to the horizon with its preset track marker and/or the runway image. In the flight path mode, the flight path marker operates as a stabilized telescope aimed toward the ground in front of the pilot; it indicates the projections of the flight path vector, manually corrected for drift, and, by its relationship to the horizon line, provides a continuous indication of roll attitude. If the angle of the stabilized telescope is depressed below the horizon at an angle equal to the sum of pitch minus angle of attack, it will be aligned with the flight path angle of the aircraft. Thus, if the marker is on the horizon, the aircraft is flying level; if below, the aircraft is descending and if above, it is climbing. The marker is thus used as a gunsight: when it is positioned over a ground target (in VFR) or symbolic representation (IFR), it indicates that, at that instant, a direct line of sight between the ground target and the pilot's eyes and defines an impact or termination point for the aircraft's instantaneous flight path. With this aiming information, the pilot is free to maneuver the aircraft as he deems appropriate in order to align his aircraft with the runway and set up a desired glide path. At his option, a reference dot and lines indicating the relative position of the ILS glide path and its upper and lower limits can be switched on.

In its final design, the projection display system under consideration will provide for flareout and touchdown control. Down to 200 feet, the pilot would aim the aircraft at the runway touchdown reference point, as indicated above. Below 200 feet, a terrain clearance reference line driven by a radar altimeter, would appear at the bottom of the display and move upward toward the horizon line as the descent continues, its displacement from the horizon line indicating wheel clearance to the ground. A flareout technique suggested by Sperry is as follows:

> "When its [the terrain clearance line] position crosses the aiming point on the display, the pilot leaves the fixed aiming point with the aircraft cue [flight path marker] and follows the intersection of the terrain level line and the runway centerline as this intersection proceeds upward in the display. At a preset point, indicated by [a little cross line on the runway centerline], the pilot ceases to follow the moving intersection and settles on the fixed cross as the new target. He holds this till wheels touch." (20)

The foregoing is intended to provide a general illustration of an approach and landing by reference to non-programmed situation displays. Similar concepts are applied in other display systems, but a variety of features and presentation techniques are being considered. The technique being explored by the Ames group in simulator studies allows for considerable flexibility and, again, reflects the basic concept:

> "The pilot can approach with as steep or as shallow a flight path as he wants to. He can approach toward a point short of the runway and then flare to a point just beyond the threshold. Or he can make a long, shallow, no-flare landing. He can make any type of landing that he can VFR; there is no programming in the display, no commands." (7)

As an extension of provisions for this kind of flight control technique, mention should be made of predictor displays. It has been pointed out (27) that time constraints on the final assessment of the approach and execution of the landing maneuver will be rather severe, e.g., an estimated 15 secs. will be available for the landing sequence from 100 feet to touchdown. Considerations of pilot time requirements for detecting an error and identifying appropriate control actions lead to a requirement for information concerning the future performance of the landing system if established values of control parameters remain unchanged. Such predictive displays augment the pilot's continuous efforts to "stay ahead of the airplane" with computed information reflecting error in the projected flight situation. Similar computations are involved in the generation of command or flight director readouts, but in the technique under consideration the predicted flight situation is displayed and the pilot is free to take any control action he considers appropriate to avoid a predicted error situation.

4.3 AUTOMATIC FLIGHT CONTROL

In general, automatic flight control refers to the instrumentation or mechanization of the basic control sequence outlined at the beginning of this section. A fully automated system would consist of control mechanisms designed to implement all of the necessary data gathering, decision making, and control action execution functions without human participation, except perhaps initiation, mode selection, monitoring, and deactivation functions. Partially automated systems provide control mechanisms for selected flight control functions, such as airspeed control, lateral flight path control; or the computation of guidance commands.

A number of automatic control concepts and systems are currently under development or study which are concerned with various techniques for achieving flight control objectives associated with the basic landing sequence. For convenience, these techniques are briefly discussed in terms of distinguishing technical features and the general provisions for implementing landing functions. Specific systems, such as the Bell AN/GSN-5 or FAA Prototype system are not identified and described. Instead, an overview of the general concept and principal control technique is provided. In Appendix A, a more detailed discussion is presented of automatic techniques for implementing each of the basic landing functions.

4.3.1 Augmented Fixed Beam Ground Transmission and Airborne Receiver Technique

The concept of this type of system is to a large extent based upon the use of ILS facilities with additional airborne equipment to provide an augmented glide slope and flareout computer for providing flareout control. The aircraft makes a normal ILS intercept and final approach vertical and lateral guidance is provided through the autopilot couplers from signals received from the glide slope and localizer receiver. An improved (Category 3) type of localizer will provide lateral guidance all the way to touchdown. Below a certain altitude, which varies with the installation and the equipment, glide slope beams become overly sensitive and unstable and are thus unsuitable as the sole vertical guidance reference where it is essential that airplane attitude and rate of sink be established prior to the landing flare. To provide this stability, glide slope augmentation circuits will be incorporated in the airborne landing computer which will essentially provide an "extension" of the glide slope until the point where flareout is initiated. One system of this type does not use the glide slope beam as the primary source of vertical guidance information but uses rate of descent from an instantaneous vertical velocity sensor as the basic parameter for aircraft vertical guidance. In this system as the aircraft deviates from the glide path a new rate of descent is commanded until the aircraft remains centered at a constant rate of descent on the glide slope beam. The general system configuration and sequence of events is illustrated in Figure 16.

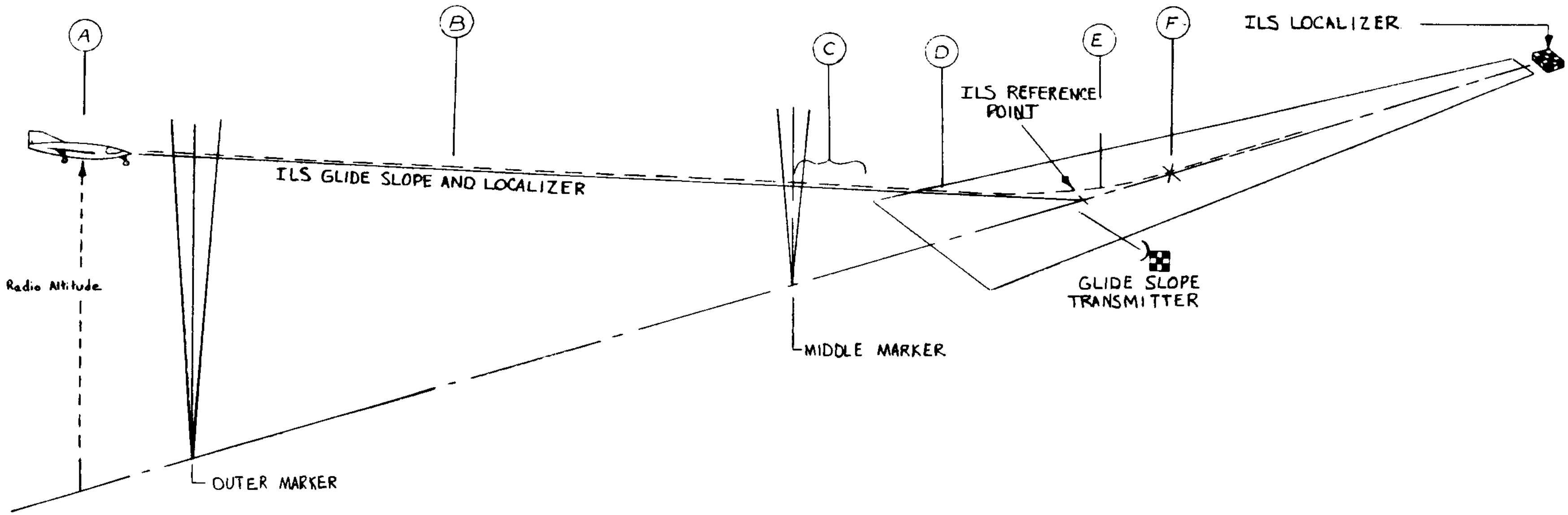
The augmented glide slope extension is initiated at some pre-determined altitude and from that point on the aircraft is either held at a constant pitch attitude or sink rate which was computed over some period of time prior to reaching the point of glide slope extension initiation. In both of these cases, that is, in maintaining an average sink rate or pitch attitude, the flight path usually is smoothed by some type of vertical velocity sensing system. In the case of the system which uses sink rate as the primary method of vertical velocity control rather than the glide path signals, the effect of the glide path is gradually washed out until such time as flareout is initiated.

Flareout is initiated at a predetermined altitude and in systems of this type an exponential flare maneuver is performed. The flare path is continually computed as a function of altitude and rate of descent to control the aircraft to a sink rate of approximately 2 feet per second at touchdown.

As in most other automatic flight control systems this type of system can use an independent airspeed control and decrab subsystem, and systems of this type have been successfully flown with both automatic control for airspeed and decrabbing.

4.3.2 Precision Tracking Ground Radar and Airborne Decoder Technique

The concept of this type of system is to a large extent based upon the use of ground equipment, with precision tracking radar as the heart of the system. The precision automatic tracking radar illuminates a pre-selected window or acquisition gate in space and automatically locks on to the aircraft as it passes through this window. The radar automatically tracks the approaching aircraft and measures its range and angles of azimuth and elevation. A ground computer makes a constant comparison of the aircraft's position with a predetermined approach path. When deviations from the desired flight path occur the necessary flight control signals are automatically transmitted to the aircraft. The



Point or Segment	Event or Function	Reference	Discussion
A	ILS intercept and approach	-	Normal ILS intercept - automatic throttle may be engaged - ALS system checks made
A - C	ILS Coupled final approach	-	Lateral guidance to touchdown through ILS coupling
B	Engage landing system	$\approx$ 500 ft.	Guidance signals still provided by ILS
C	Glide slope extension initiated	200 - 100 ft.	Radio altimeter initiates command
C - D	Glide slope extension	2 - 3 sec.	Constant pitch or rate of descent maintained
D	Initiate flareout	$\approx$ 100 ft.	Radio altimeter initiates command
D - F	Automatically Controlled Flareout	-	Exponential flare as a function of altitude and rate of descent
E	Initiate decrab	$\approx$ 15 ft.	Radio altimeter initiates command
F	Touchdown	-	Variable

Fig. 16 Augmented Fixed Beam Approach and Landing

transmission is via data link which may be either the conventional ILAS transmitter receiver system or a unique transponder-receiver-decoder system. The control signals are decoded and fed into the autopilot coupler for aircraft control. During approach and landing the altitude of the aircraft is automatically controlled by commanding changes in pitch attitude and the lateral guidance is controlled by commanding changes in bank angle. The general system configuration and sequence of events during landing is presented in Figure 17.

No specific automatic throttle control subsystem or airspeed control subsystem is associated with the over-all flight control system, and any appropriate speed control system might be used.

Flareout can be initiated by the ground computer on the basis of a specified time to touchdown, or at a predetermined altitude.

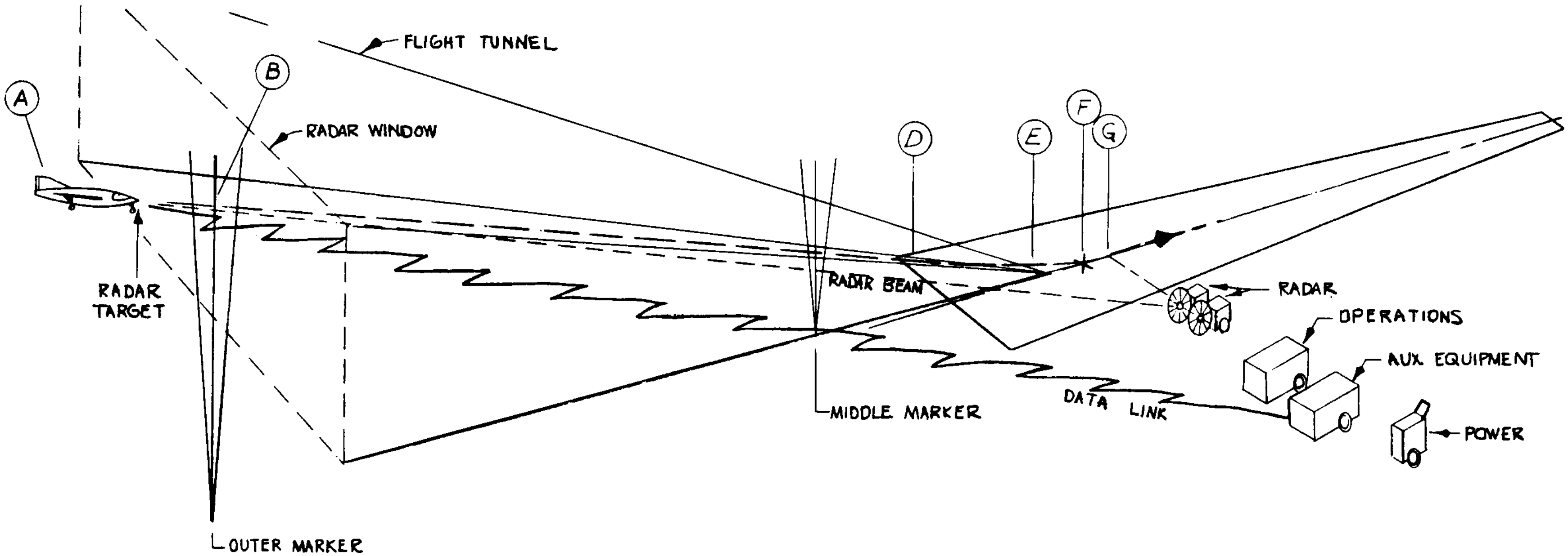
The decrab maneuver is also initiated by the ground computer as a function of time to go (or altitude). The maneuver is initiated as close to touchdown as possible to avoid lateral offsets which will result through the generation of the side slip angle. Predetermined rudder and bank commands necessary for decrab are used in the computer.

Touchdown point is variable as the aircraft is continuously controlled to touchdown at a predetermined sink rate (usually about 2 feet per second).

No automatic control is provided for roll-out guidance although presumably some radar guidance could be available, depending on the location of the transmitter and touchdown point.

The waveoff capability can be either manually initiated by a ground console operator or automatically initiated by the system. If automatic waveoff is commanded level flight commands will be imposed on the autopilot since the gyros will return to their reference values. As the aircraft attitude changes in response to these commands the attitude change will initiate a thrust command.

The basic operation of a typical Precision Tracking Ground Radar and Airborne Decoder Equipment System is shown in the block diagrams of Figures 18 and 19.



Point or Segment	Event or Function	Reference	Discussion
A	Air Traffic Control Navigation	Terminal Approach Altitude.	Any ATC terminal feeder system may be used
B	Radar Acquisition	4 miles out	Radar Window is ± 5000 ft. lateral range; ± 400 ft. altitude; 1200 ft. range
D	Initiate Flareout	≈14 sec. to go	Exponential Control; Time to go computed in ground equipment
E	Decrab	2-4 sec. to go	Time to go computed from ground
F	Touchdown	Sink rate 2/ft/sec.	Touchdown point is variable based on aircraft configuration and wind conditions
G	Disengage	Lose lock on	Radar returns to search mode as aircraft passes radar on roll-out
B - D	Vertical Guidance Control	Continual from lock on.	Pitch commands transmitted from ground
B - F	Lateral Guidance Control	Continual from lock on.	Bank commands transmitted from ground
A - D	Constant Airspeed Maintained	Pre set IAS	Airspeed and pitch attitude as inputs
D - F	Airspeed bleed-off	Touchdown IAS	Airspeed is gradually reduced to desired touchdown IAS

Fig. 17 Precision Radar Approach and Landing Control

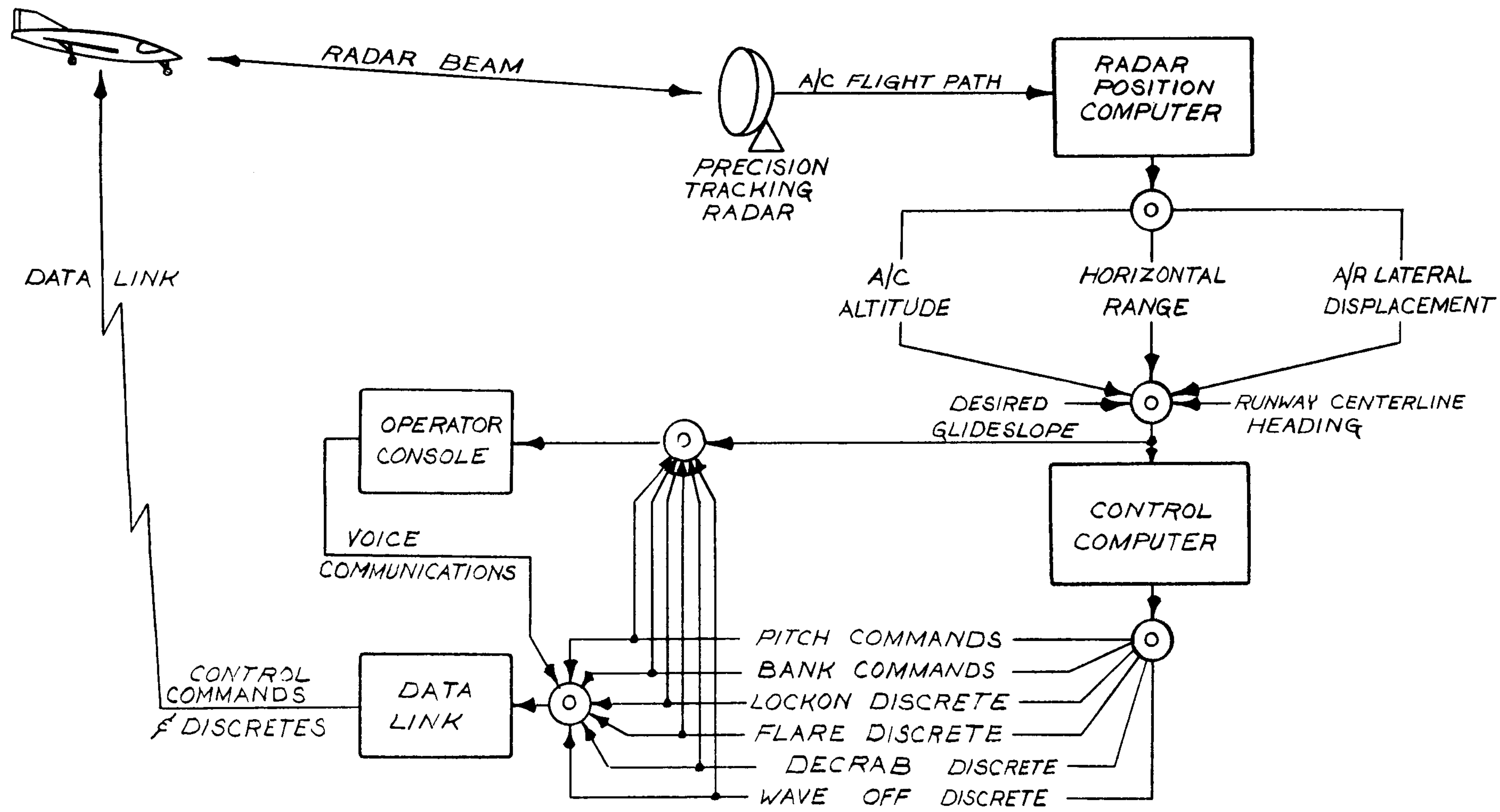


Fig. 18 Radar Ground System Operation for Approach and Landing

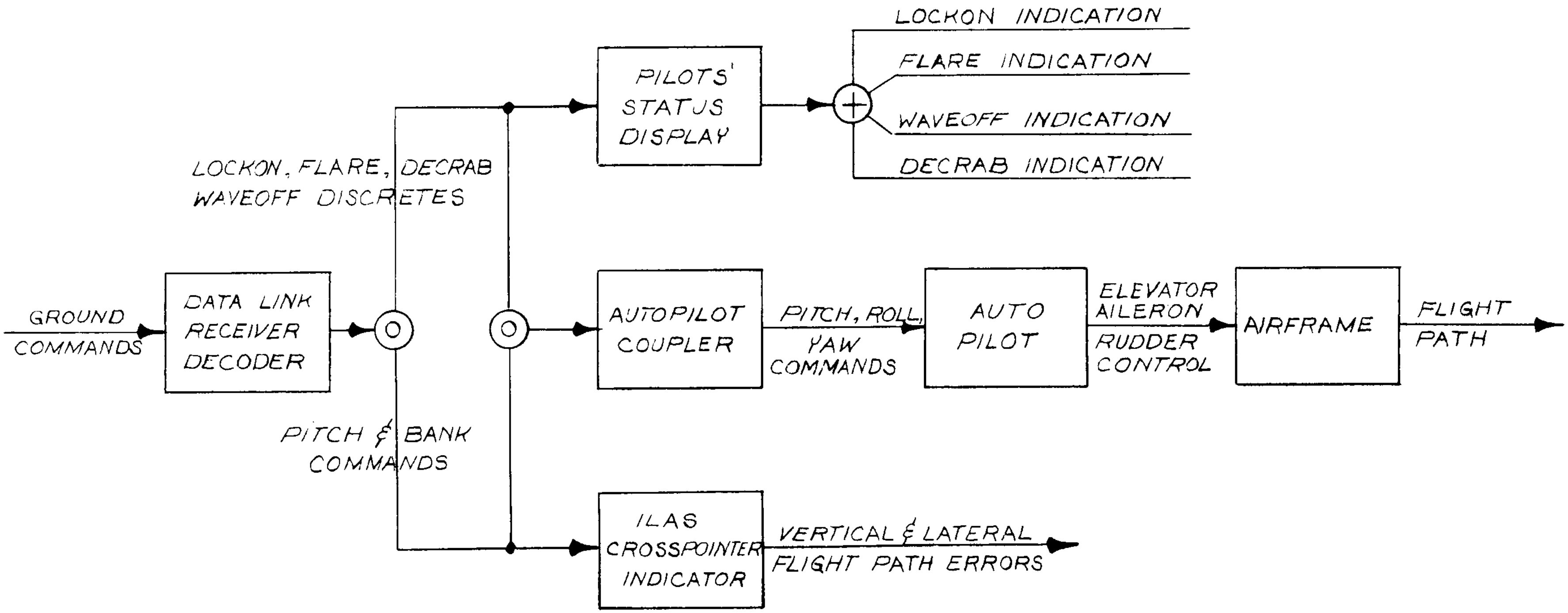


Fig. 19 Airborne Equipment Operation for Radar Approach and Landing

4.3.3 Scanning Beam Ground Transmission and Airborne Decoder Technique

The Scanning Beam Ground Transmission and Airborne Decoder type of automatic landing system is primarily a ground based microwave system which transmits coded guidance data to the aircraft from a continuously scanning ground antenna. There are two types of scanning beam systems which appear to have undergone the most extensive development work. These two types of systems may be classified as the Biangular Technique and the Range-Angle Technique.

Both systems could be implemented in three ways: (1) completely independent of ILS, (2) in conjunction with ILS, or (3) for final vertical guidance and flareout only. The concepts underlying the Biangular Technique and Range-Angle Technique are presented separately below.

4.3.3.1 Biangular Technique

This technique was originally conceived of as employing two antennae and transmitters for vertical scanning and guidance, one for the approach angle and one for the flareout angle (See Figure 20) and one transmitter and antenna for lateral scanning and guidance (not shown in Figure 20), plus airborne equipment. While the complete technique is feasible, recent development and test efforts have been directed toward utilizing the system with an improved ILS glide slope beam and narrow beam localizer. The description that follows is based on this more evolutionary approach.

The Biangular Technique for all-weather landing is designed to supplement the ILS system with accurate vertical guidance and flareout data. A normal ILS intercept is executed by the pilot and vertical and lateral guidance for final approach are provided by the ILS glide slope and localizer beams through an autopilot coupler mode. The scanning system takes over at initiation of flareout, although the system is such that pre-selected angular beams for initiation of flareout and terminal glide angle can be received and monitored as far out as 20 miles from the scanning transmitter. The general system configuration and sequence of events during landing is presented in Figure 21.

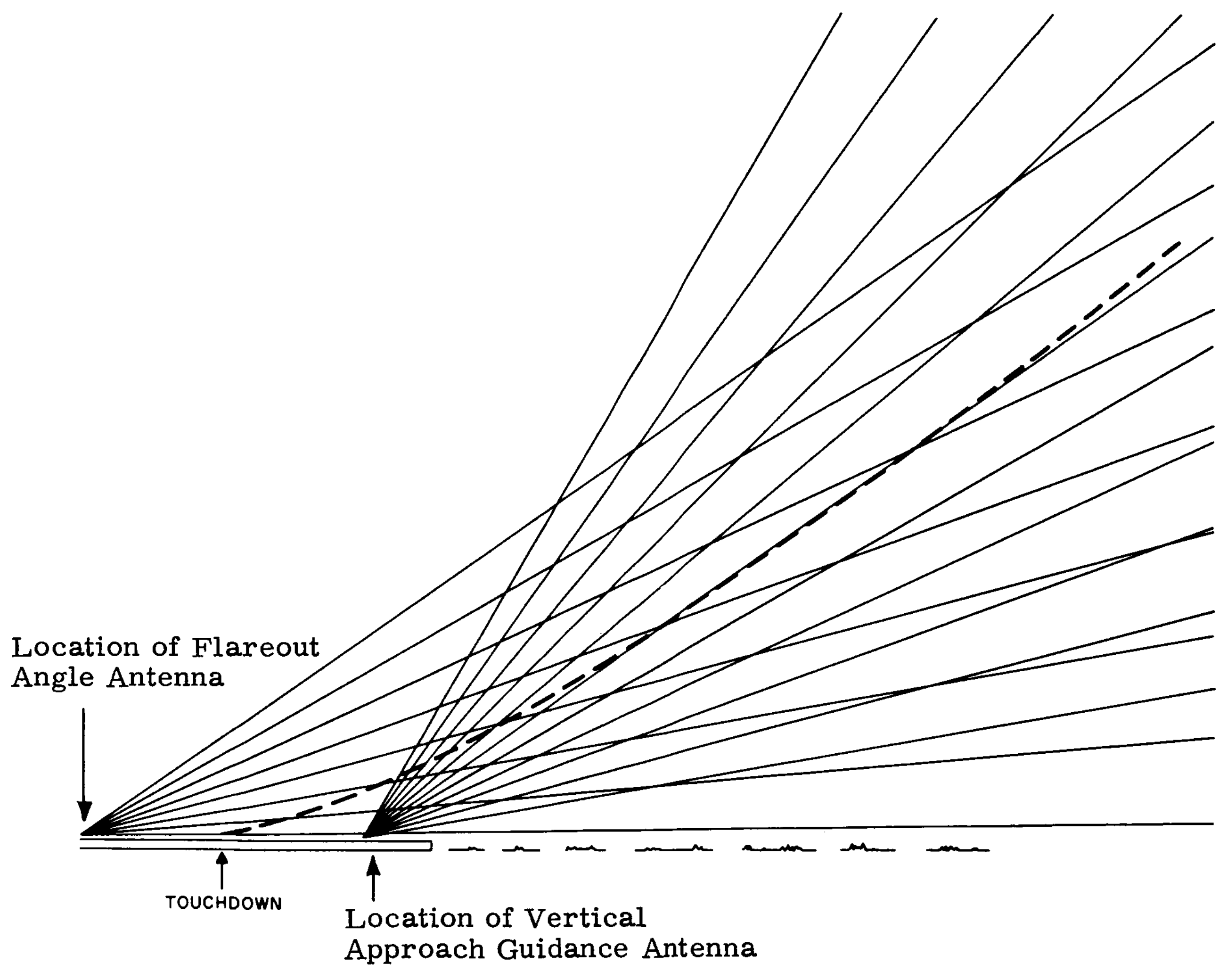
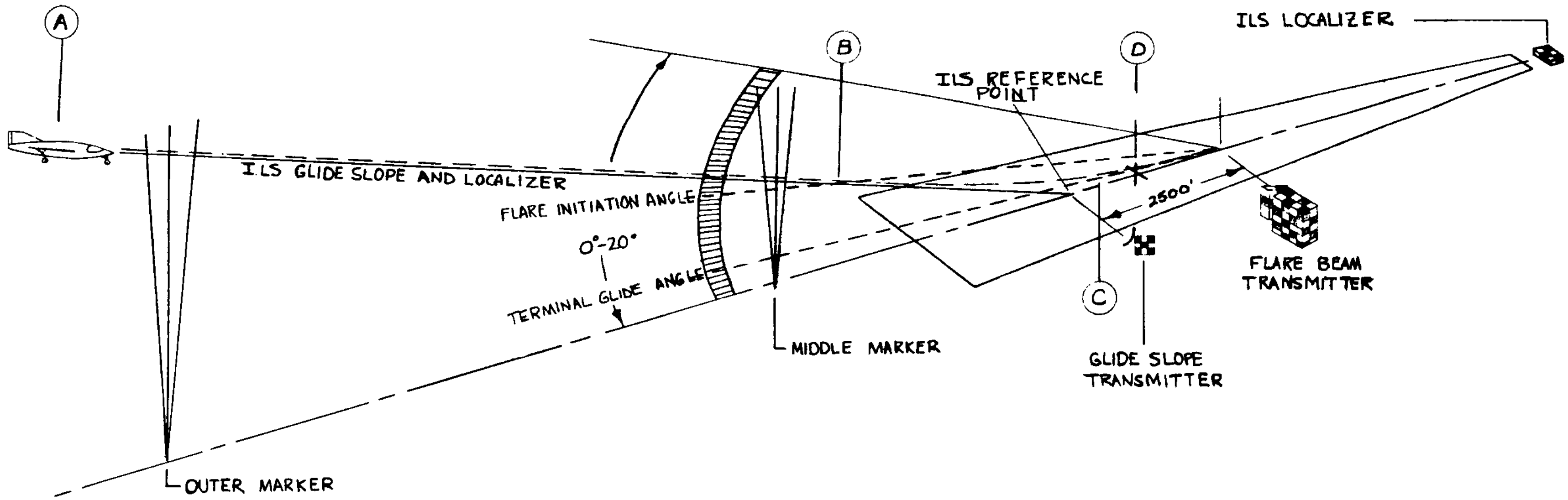


Fig. 20 Dual Transmissions for Approach and Flareout



Point or Segment	Event or Function	Reference	Discussion
A	Normal ILS intercept and approach	-	During ILS Approach Pre-select Flare initiation angle & terminal glide angle; monitor flare beam
A - B	ILS final approach	To flareout	ILS lateral guidance to touchdown, vertical guidance to flareout
B	Initiate flareout	$\approx$ 100 feet	Flareout initiated where the two beams intersect
B - D	Flare angle controlled flare maneuver	Flare Beams	Flare angle changes gradually to terminal glide angle
C	Decrab (manually)	$\approx$ 15 feet	Decrab can signal and command can be built in
D	Touchdown	-	Touchdown in area between the two beams

Fig. 21 Bi-angular Landing Approach and Control

The continuously scanning antenna of the ground equipment,. which is located some 2500 feet behind the glide slope transmitter, transmits a continuous series of microwave beams with coded angular data correct within 0. 01 degree. These beams are transmitted over an angle of 0 to 20 degrees. Encoded angular data is received by a special airborne receiver which decodes the data and can be used to provide guidance information to autopilot coupler for automatic operations as well as drive a Zero Reader type of display. At the point where the pre-selected flareout beam intercepts the glide slope, the flareout maneuver is initiated and a smooth exponential transition to a pre-selected terminal glide angle is executed with vertical guidance provided all the way to touchdown. No features are provided for automatic airspeed control, decrab or go-around, although this type of system has been flown with an automatic airspeed control. The basic operation of a typical Biangular Scanning Beam System is shown in the block diagrams of Figures 22 and 23.

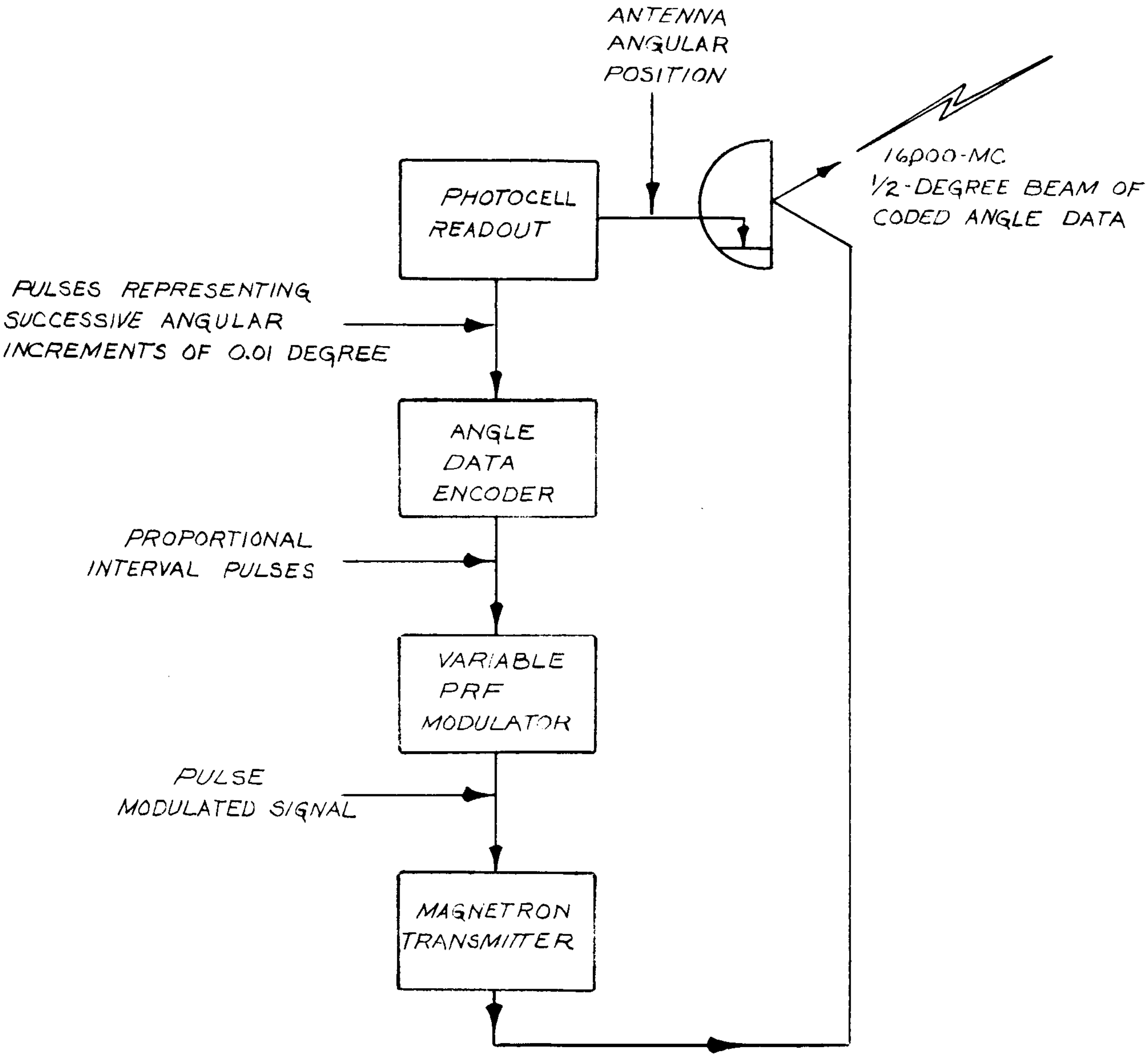


Fig. 22 Functions of Ground-Based Equipment for Bi-angular Approach and Control

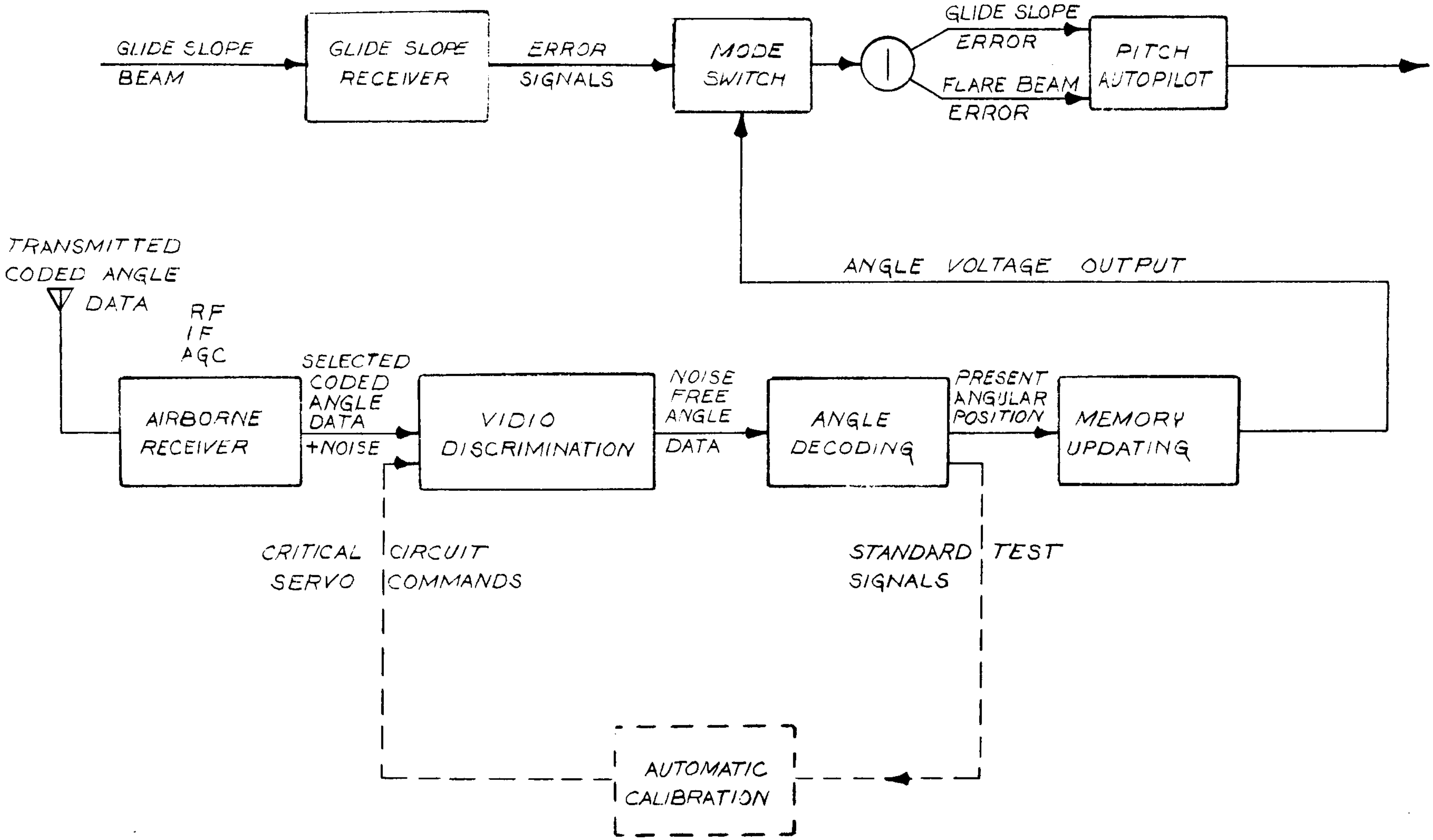


Fig. 23 Functions of Airborne Equipment for Bi-angular Approach and Control

4.3.3.2 Range-Angle Technique

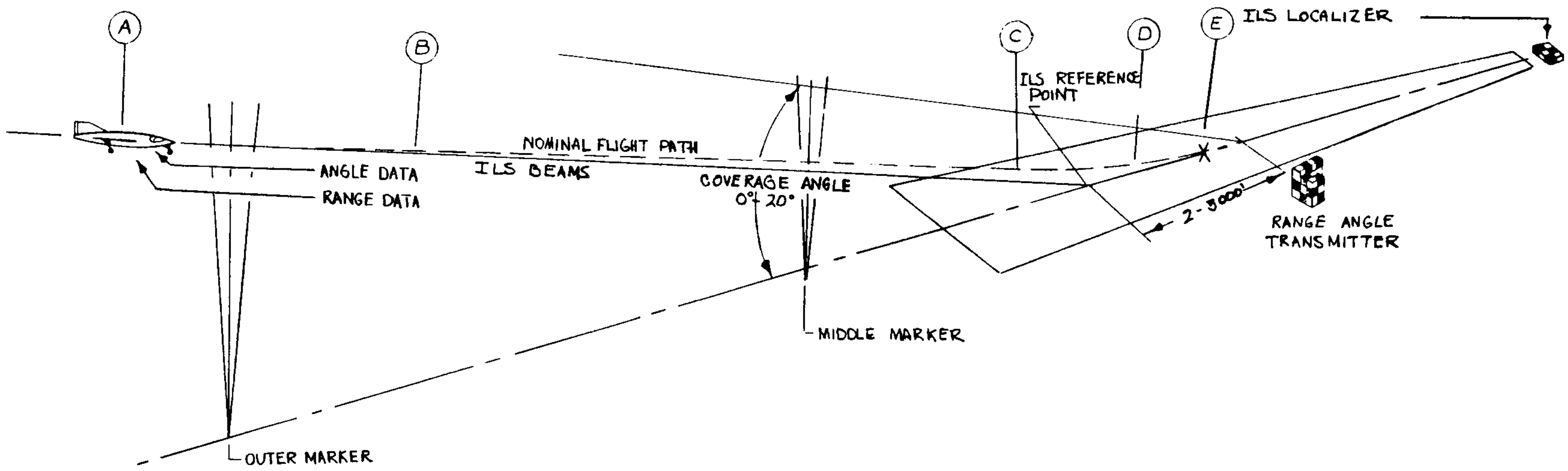
This technique was originally conceived of as employing a notched scanning beam and DME for vertical guidance and a similar azimuth angle system for horizontal guidance, plus airborne equipment. While the complete technique is still feasible more recent development and test efforts have been directed toward utilizing the system with an improved ILS glide slope beam and narrow beam localizer. The description that follows is based on this more evolutionary approach.

The Range-Angle technique, sometimes called Rho-Theta, is designed to supplement the ILS system with accurate vertical guidance and flareout data. A normal ILS intercept is executed by the pilot and vertical and lateral guidance for final approach are provided through the ILS glide slope and localizer beams through an autopilot coupler mode. At some time after the glide slope is intercepted the automatic Range-Angle system is engaged for pitch commands to the autopilot.

A scanning beam microwave transmitter located near the touchdown point provides coded angle reference signals to all aircraft in the approach and landing airspace. The airborne unit measures the range-to-touchdown by interrogating the ground equipment in a manner similar to DME. The airborne equipment receives and reads out the angle data at the instant the scanning beam is pointed directly at the aircraft. The general system configuration and sequence of events during landing is presented in Figure 24.

The system makes precision range and elevation angle information available in the aircraft throughout the entire approach, flareout and touchdown maneuver. Altitude and altitude rate information is readily derived for flight control systems which use these variables. Since the system is basically a source of position information, various combinations of path computers, displays and other guidance elements can be used with Range-Angle technique to form an operational landing system. The basic operation of a typical Range-Angle Scanning Beam system is shown in the block diagrams of Figures 25 and 26.

No provisions are specifically provided for decrabbing or airspeed control although the system has been successfully flown with an automatic airspeed control.



Point or Segment	Event or Function	Reference	Remarks
A	Normal ILS intercept	-	ILS lateral guidance utilized until touchdown
B	Engage tracking mode	After OMM	Tracking mode is engaged after crossing outer marker on ILS
B - C	Regal Beam vertical guidance	Continuous	Constant rate of descent until flareout
C	Initiate flareout	≈100 feet	Flareout initiated at a pre-selected altitude
C - E	Flareout maneuver	-	Exponential control utilizing altitude and rate of descent
D	Decrab	≈15 feet	Decrab signal and command can be built in
E	Touchdown	-	Touchdown point is variable

Fig. 24 Range Angle Approach and Control

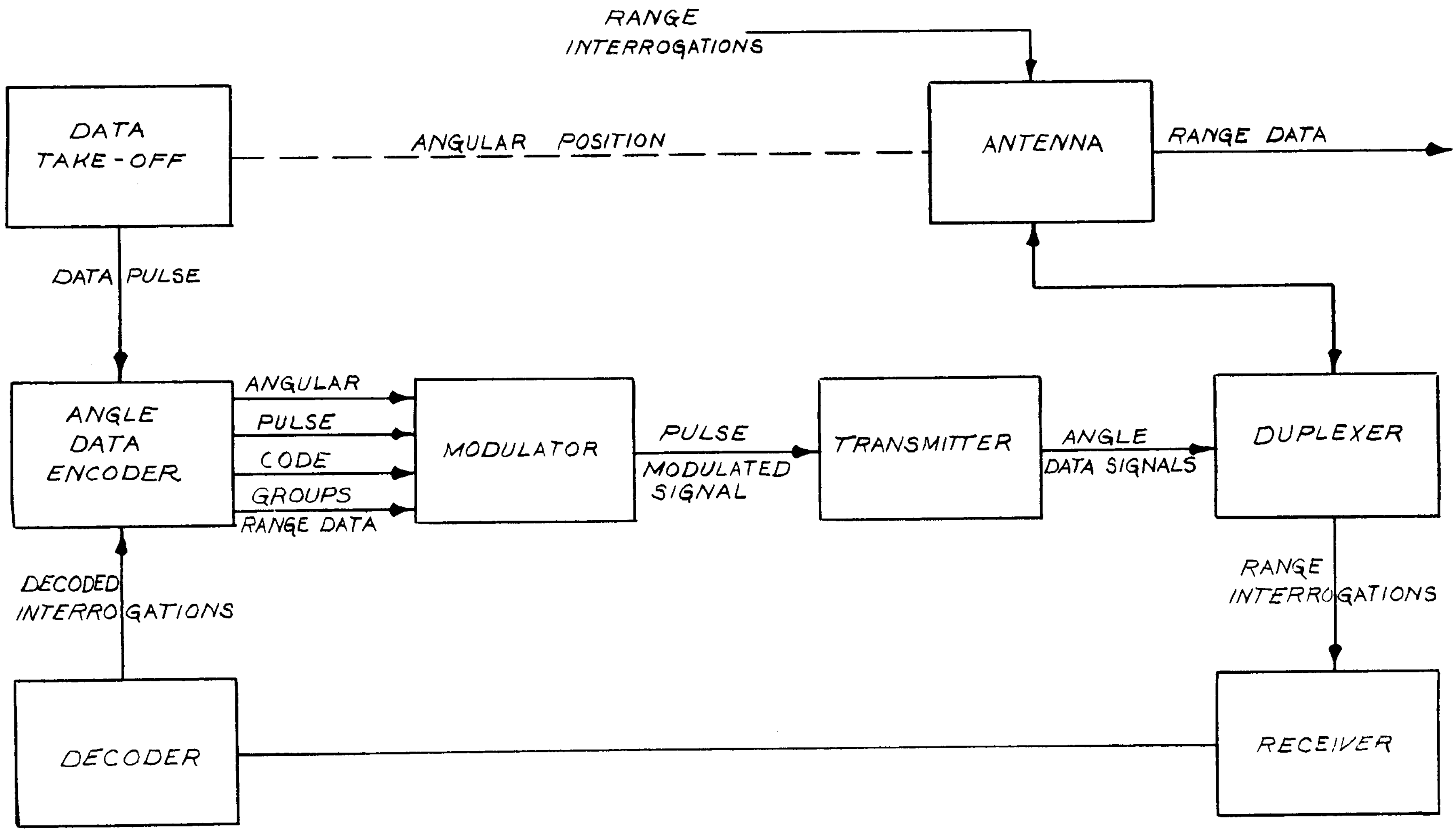


Fig. 25 Range-Angle Transmitting Set Block Diagram

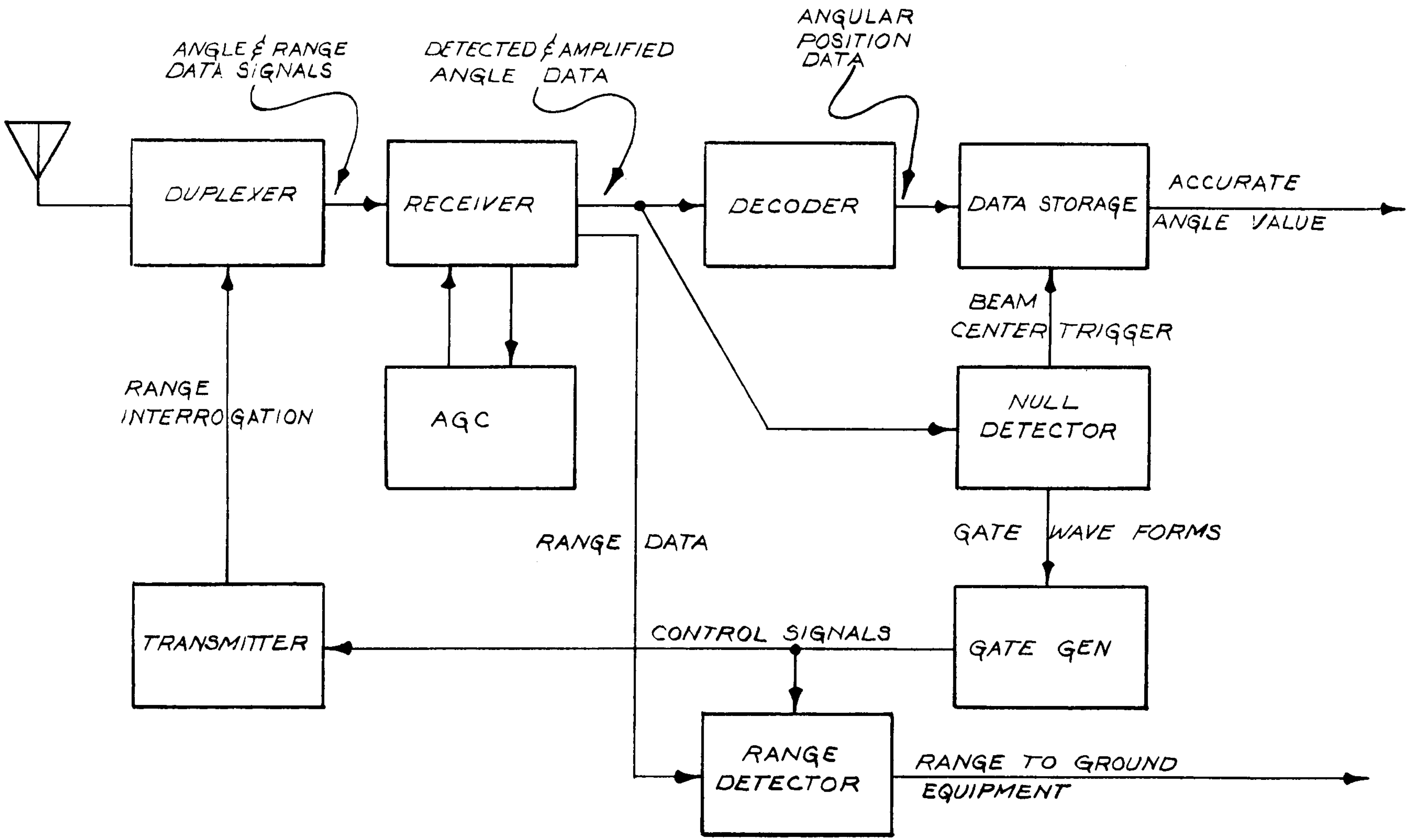


Fig. 26   Range-Angle Airborne Equipment

4.3.4 Scanning Beam Rectangular Coordinate Technique

This technique was presented in a recent study for the Air Force (10). Excerpts or paraphrases from that study are used below to describe the concept.

> "The scanning beam system provides rectangular coordinates of position. The system employs three notched scanning beams. A coordinate system of unique fix-lines parallel to the runway are provided by scanning two beams in the vertical direction about axes which are parallel to the runway. [See Figure 27.] These fix-lines enable the aircraft to determine its elevation and lateral deviation about the runway centerline. Longitudinal position along the runway (or runway extended) is derived by a third beam which scans horizontally and intersects the parallel system of lines.
>
> "This system automatically controls an aircraft throughout the entire landing maneuver from the point of acquisition to the completion of ground roll, without the aid of existing guidance systems, e.g., ILS and AGCA. However, it is flexible and will operate with such existing systems if desired. The functions to be performed include acquiring the aircraft in an area five to ten miles from the airport, presenting information for manual or automatic guidance, based on position data that becomes increasingly more accurate as the aircraft approaches the runway, and providing information for manual or automatic flareout and ground roll control.
>
> "The system employs radio-position-fix measuring equipment as the data source. A portion of the radio-position-fix equipment develops a coordinate system of fix lines that is unique because the lines are parallel to the centerline of the runway. This enables the aircraft to determine its elevation and lateral deviation from the runway centerline - the most important components of position information - without the use of DME. The lines are generated by a pair of scanning beam antennas,

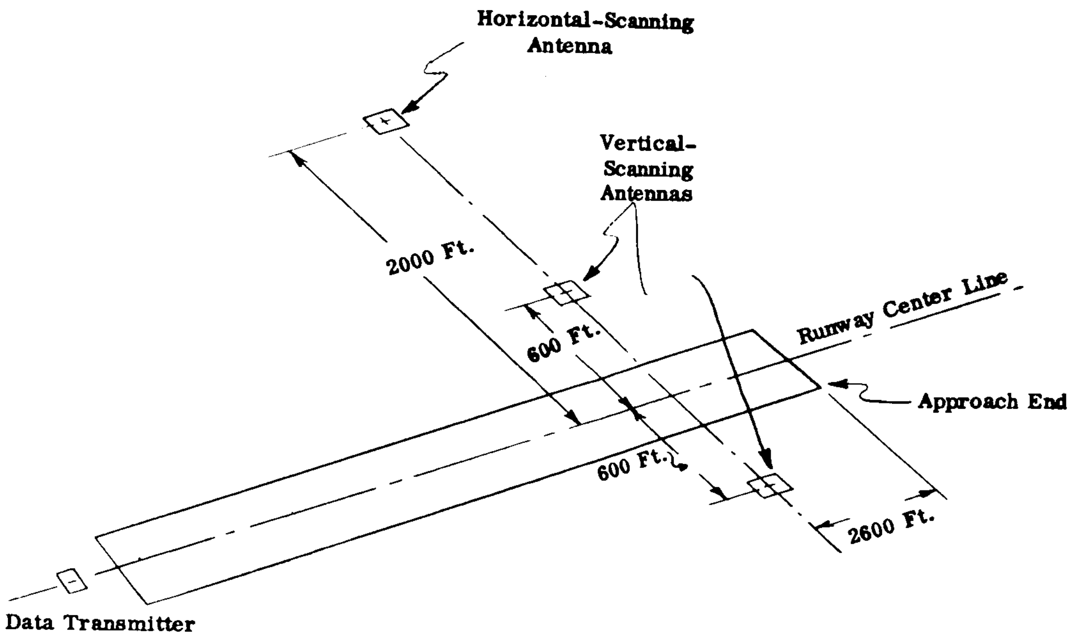


Fig. 27 Antenna Locations for Rectangular Coordinate System

(Taken from Reference 10)

each radiating a fan-shaped beam that is scanned in the vertical direction about an axis parallel to the runway. Longitudinal position along the runway (or runway extended) is derived by a third fan beam which scans horizontally and intersects the parallel system of lines. A sketch of the three beams is shown in Figure [28.]

"To implement the rectangular coordinate system, four low-powered transmitters, including an appropriate power source, with three scanning antennas for fan-beam generation and one angle-data antenna are required at each air terminal. The philosophy of the technique is to keep the airborne equipment to a minimum without sacrificing performance or reliability. The complexity of the equipment to be installed in each aircraft need only be that governed by the amount of automatism desired by the aircraft's owner. See Figure [29] for a simplified block diagram of a completely automatic system."

The report suggests the following advantages for the system:

"a. It provides three-dimensional position-fix information in rectangular coordinate form. These coordinates are altitude above the runway, lateral deviation from the runway centerline, and longitudinal position along the runway centerline (or centerline extended).

"b. It provides three-dimensional position-fix information through a data receiver without requiring the use of DME or radio altimeter.

"c. It provides the aircraft with crab-angle and ground-roll guidance information."

4.3.5 Airborne Tracking Radar and Attitude Sensing Technique

This technique was presented in a NASA analog simulation study (1). Excerpts or paraphrases from that study are used below to describe the concept.

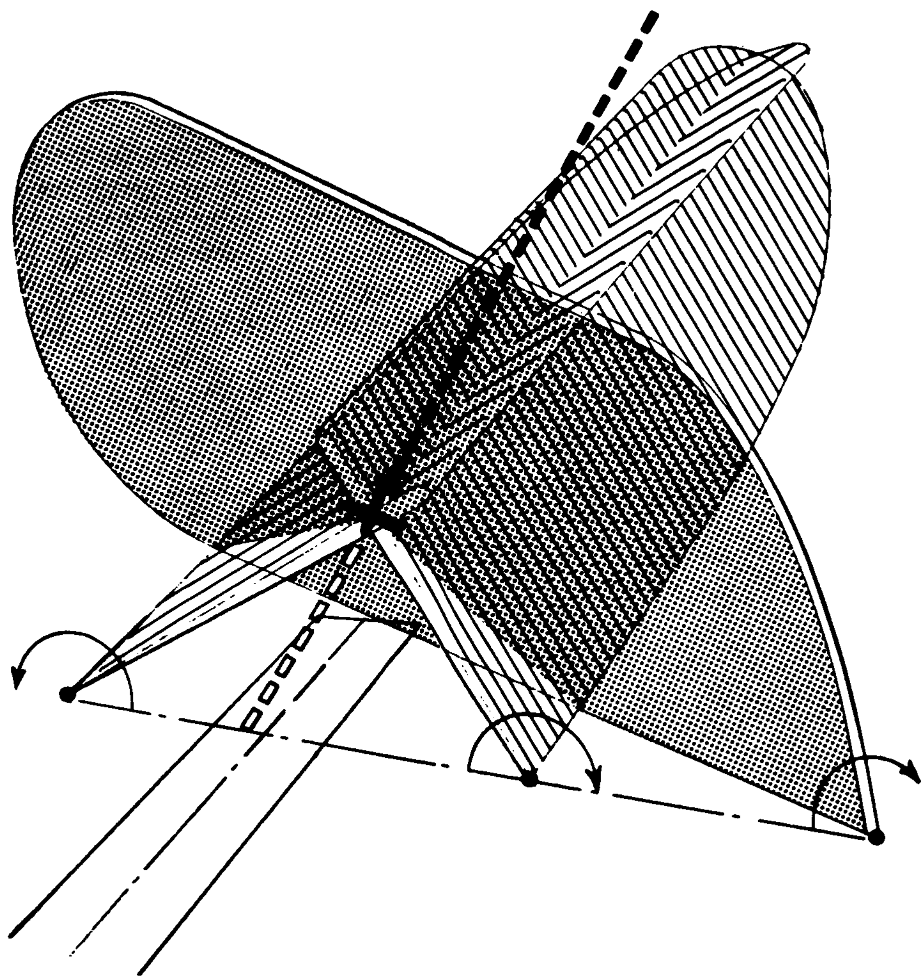


Fig. 28 Pattern Diagram of the Scanning Beams

(Taken from Reference 10)

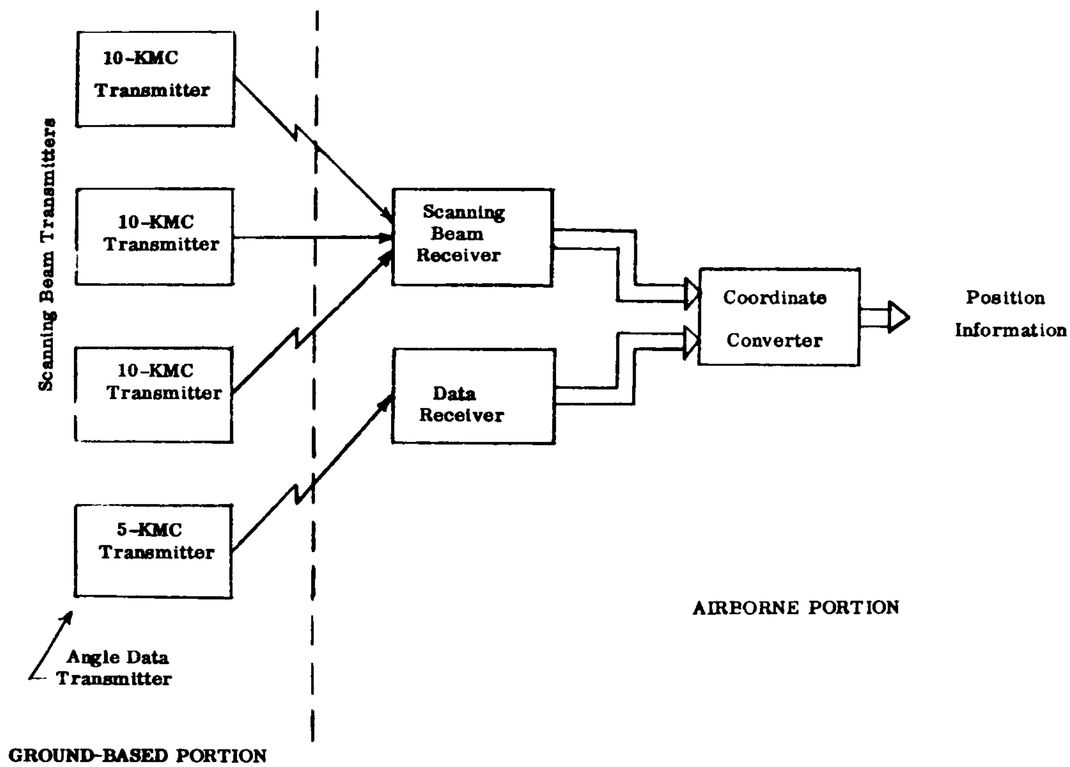


Fig. 29 Rectangular Coordinate System, Simplified Block Diagram

(Taken from Reference 10)

"Analysis indicates that it is possible to control an airplane in a landing-approach maneuver by means of an automatic control scheme which derives its error signals from airborne attitude-measuring equipment and airborne radar equipment tracking a target located at the end of the runway. An analog study has been made of such a system. A swept-wing jet fighter airplane was represented by six-degree-of-freedom equations with linear aerodynamic coefficients. The radar and attitude information was assumed to be free of any lag or dynamics. The control system using these radar and attitude measurements appears to be feasible.

"Approach systems that are presently in use, such as ILS and AGCA systems, require complex equipment on the ground. In contrast to these systems, an automatic approach system may be devised using a simple radar target on the ground and the radar tracking set and attitude-measuring equipment in the airplane. The simplicity of the ground equipment required in such a scheme could, in itself, be a worthwhile advantage in providing bad-weather facilities for an airfield. In addition, such a system has the advantage of allowing the complex parts of the system to be adjusted to match the individual characteristics of the airplane carrying this equipment.

"This analysis deals with the problem of controlling an airplane to the landing-approach glide slope centerline using airborne equipment. Only the straight-line part of the approach is considered. The final flare and touchdown is not considered in this analysis. The airplane was assumed to be equipped with a tracking radar or similar target-seeking equipment capable of establishing the line of sight between the airplane and a target located at or near the approach end of the runway, and attitude gyros which can measure the pitch, roll, and direction angles of the airplane. It was assumed that the rudder, ailerons, throttle, and elevator controls would be used to control the airplane, and that various outputs of the airplane, attitude gyros, and radar, would be used to position these controls.

APPENDIX A
AUTOMATIC TECHNIQUES FOR IMPLEMENTING EACH LANDING FUNCTION

This appendix describes some automatic techniques under consideration for implementing each of the basic landing functions identified in Section 3.3. It was necessary to identify and describe various techniques for implementing landing functions in order to develop the basic technical data necessary for development of questionnaire items and the subsequent data analysis. This appendix was thus compiled in order to document useful reference information which was collected to support the research effort. No attempt has been made to identify or describe techniques attributable to any particular avionics equipment manufacturer although the techniques are in general representative of efforts by various industries or government organizations. The techniques described in this section may be considered as engineeringly feasible in the near future and thus to represent possible techniques about which we are concerned with collecting pilot acceptance data. The basic requirement or definition of each function developed in Section 3.3 is presented first for each function and various techniques for implementing the function are then described.

Technical information has been freely copied for inclusion in this appendix. The material here is in "working paper" form, and as this is not a final or official report no claim is made as to completeness or evenness of coverage.

A.1 ACQUISITION OR INITIATION

Acquisition or initiation refers to the method by which the aircraft and/or pilot engages the terminal area approach and landing guidance system. Typically an aircraft descends from a let down position fix to an initial approach altitude on a heading, which is maintained until the approach guidance system is acquired or initiated. The lateral guidance function will usually be engaged first and followed by initiation of the vertical guidance function. Airspeed control for approach and landing will also be initiated during the initial approach/acquisition segment.

All of the automatic landing techniques under consideration require the pilot to perform several tasks manually which have not been considered for automation at this point. These tasks include such things as:

(1) establishing an initial approach attitude, altitude, and heading

(2) setting and utilizing flaps as desired

(3) lowering the landing gear

(4) establishing an initial approach air speed

(5) setting the desired runway heading on the flight director, horizontal situation indicator, or other instruments.

In addition to these things the pilot must (1) turn on airborne systems involved in automatic landing, (2) monitor the performance of these systems, (3) select flare-out angles in the case of the scanning beam transmitter type systems, (4) disengage the automatic landing systems.

A.1.1 ILS Intercept Techniques

Since the Instrument Landing System (ILS) is one of the most frequently cited methods for implementing certain automatic landing system functions, a brief discussion of the technique for engaging and intercepting the ILS localizer and glide slope beams is presented here. This discussion has primarily been abstracted from a recent report prepared by the Radio Technical Commission for Aeronautics Special Committee 79 (26).

During a standard approach to the ILS system the aircraft would intercept the localizer first at a distance of at least 10 miles away from the airport and fly the localizer beam at a constant altitude until the glide slope was intercepted and then initiate a constant rate of descent maintaining the aircraft on course both laterally and vertically. Interception of the localizer and glide slope are described separately, as follows:

"In a typical intercept, the aircraft would approach the Localizer course on a constant heading at least three miles beyond the Outer Marker. As the cross pointer comes off the stop, the approach system would be engaged. In the case of an approach made relatively close to the Outer Marker at a high approach angle, the aircraft would immediately roll to its maximum permitted bank angle. This bank angle would be held until the aircraft heading approaches the heading of the runway. This kind of interception is quite independent of the Autopilot/Coupler characteristics because the aircraft is at its maximum bank angle most of the time. In the case of an approach made at a shallow heading angle and relatively far from the runway, the aircraft will not achieve maximum bank angle and the character of the response is largely determined by the coupler gain and damping characteristics."

ILS glide slope acquisition can be separated into three phases consisting of (1) the initial conditions, (2) the transient phase, and (3) the steady state phase. The initial conditions are defined as the steady state flight conditions existing immediately prior to the maneuver and necessary for acquisition of the glide slope. In a typical initial approach the aircraft is stabilized at a constant altitude above 1000 feet. The initial airspeed is set up dependent on the flying characteristics of the aircraft. The transient phase starts at the beginning of the pitch over maneuver and ends when the aircraft is stabilized on the glide slope. It is undesirable to be in the fly up direction. The steady state phase consists of stabilized flight along the glide slope. Lateral control should be stabilized by the time the aircraft reaches the Outer Marker and minimum stabilization distance of 3 miles should be allowed.

A.1.2 Augmented Glide Slope Technique

Augmented glide slope systems require a normal ILS intercept and ILS approach until some predetermined point when the augmented glide slope technique is initiated, thus the augmentation feature of the system must be turned on prior to initiation of glide slope extension but the aircraft will be under fully automatic control through a typical ILS approach coupler before then.

A. 1. 3 Precision Tracking Radar Technique

Precision automatic tracking radar systems illuminate a preselected area in space known as an acquisition gate or window. This window will be located at some point near or beyond the outer marker on the extended run-way centerline. The aircraft must fly through the gate (this can be done by flying the localizer beam from a much farther distance out) and as the aircraft passes through the gate the radar locks on to and automatically tracks the aircraft. Tracking will probably be enhanced by equipping the aircraft with a beacon or corner reflector to provide a point target for the precision tracking radar.

a. 1. 4 Scanning Beam Transmitter Technique

Scanning beam transmitter systems are not currently used for final approach guidance and thus initiation or acquisition of the system does not occur until flareout A normal ILS intercept is made and the ILS is followed until the scanning beam system takes over at flareout. For this technique the system must merely be turned on and guidance signals are automatically switched from ILS to flare beams at the flareout initiate point. The flare system is capable of being monitored from distances of 10 to 20 miles away from the airport.

A. 2 AIRSPEED CONTROL

Airspeed control is a method for controlling the thrust and/or drag of an aircraft so as to compensate for any airspeed deviations from desired or optimum values. Airspeed control is maintained from initial approach to touchdown. For typical landing operations there are three different airspeed control problems during approach and landing, namely, airspeed control during the initial approach, airspeed control for final approach, and airspeed control during flareout.

Optimum performance of any Landing System is predicated upon maintaining proper airspeeds throughout the landing sequence. Automatic systems are designed to detect and initiate rapid corrections for airspeed variations which result from wind gusts, and to anticipate and correct for those airspeed changes which would otherwise be produced by variations in the flight path. Such anticipation is possible since the change in flight path angle is proportional to the corresponding change in aircraft attitude, and the attitude change precedes the flight path change. The provision of attitude information in the throttle control system, together with the proper design of the network through which this information enters, reduces transient airspeed changes, and eliminates the steady-state changes due to variation in the flight path.

An automatic throttle control system which is relatively independent of the flight control system can be utilized prior to initiation of the automatic flight control system all the way to touchdown. The automatic throttle can be engaged and an acceptable IAS set up prior to interception of the localizer. Changes in throttle setting can be made manually up to the point where the automatic flight control system is initiated and any manual settings made will be held constant. In some systems, the automatic control is designed to maintain the aircraft at a selected airspeed throughout the approach until beginning of the flareout. At flareout the throttles are programmed back to flight idle. A constant airspeed is maintained despite any changes in aircraft configuration. In other systems, continuously variable airspeeds, selected fixed airspeed, and programmed airspeed control techniques are employed. Selected, programmed, and computed airspeeds are established and maintained primarily by commanding throttle changes and many systems include drag device activation and pitch commands. Examples of these techniques follow.

A.2.1 Constant Approach Speed and Programmed Flareout Technique

One variation of constant airspeed control techniques requires the pilot to establish a desired airspeed prior to engaging automatic control. Figure 30 provides a block diagram of this technique.

The airspeed transducers receive static pressure by connection to the existing aircraft static pressure port. Pitot pressure is obtained

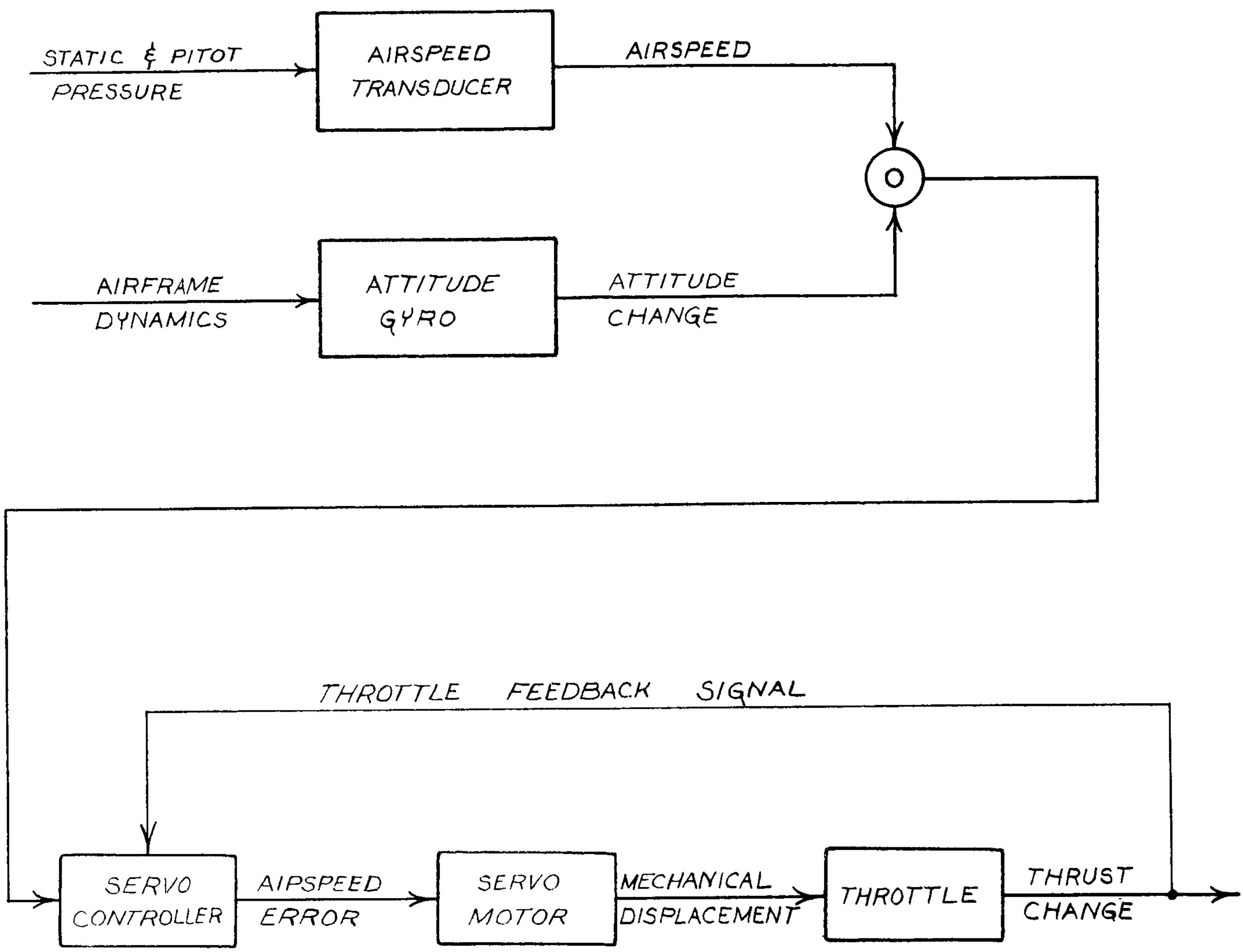


Fig. 30 Automatic Throttle Control System Operation

from the existing pitot line, and may connect directly to an acoustical filter chamber for airspeed filtering, or directly to the airspeed transducer when airspeed filtering is accomplished electronically. Aircraft attitude information is received from the vertical gyro and transmitted to the throttle system.

Prior to engaging the automatic throttle-ready switch, the airspeed and attitude signals do not enter the control system. When the pilot engages the automatic throttle-ready switch, the aircraft attitude signal, the airspeed signal, and the throttle servo loop feedback signal is transmitted to the throttle synchronizers. The difference between the attitude signal and the airspeed signal together with the throttle feedback signal are acted on by the throttle synchronizers to drive the error to zero. When the error has been reduced to a predetermined value, the pilot will be notified by a signal from the synchronizer indicators and he may then engage the automatic throttle.

During automatic throttle operation, airspeed changes are sensed as variations of voltage. This voltage variation generates an error signal in the throttle servo loops. These error signals actuate the servo motors which, in turn, manipulate the throttle to command a thrust change. The thrust change accelerates or decelerates the aircraft until the error is driven to zero. A change from the reference attitude produces a change in the output voltage of the attitude amplifier, which also causes an error signal to appear in the servo loops. A change in thrust is commanded, again via the servo motors, to anticipate and correct for the change in airspeed which would accompany the ensuing flight path change.

In another constant airspeed control technique, desired airspeeds are selected by the pilot. Engagement of the system is made by pressing a button on a mode selector panel, and is indicated by a light. Disengagement is effected by means of momentary-break-contact buttons on the outward sides of the left and right throttle levers. For safety, a micro-switch in each throttle quadrant prevents the throttle servo from reducing engine rpm below a predetermined minimum. Mechanical slip clutches in the capstans allow overriding by the pilot. In actual operation, an initial airspeed is selected for automatic control during the approach to the localizer beam, and a second airspeed is selected after engagement of the glide path beam. The third and final speed is selected for the final approach.

A throttle control system providing for control of selected airspeeds and programmed flareout is described below. The system was used for flight test evaluation of a scanning beam transmitter system using a B-25 (23). A block diagram of the throttle control system is presented in Figure 31. Its operation was described as follows:

> "During the approach, airspeed is controlled to a preselected constant value that is set in by the pilot. Pitch attitude is used to damp the phygoid mode, and the minimize errors during pitch transients. In the flare, the original instrumentation consisted of an airspeed program as a function of altitude (in the case of the Angle-Range technique) or as a function of elevation angle (in the case of the Biangular technique). While this worked reasonably well on the B-25, computer studies of a similar program applied to a large jet transport indicated poor stability and probably unacceptable performance. The engine time lag, which is fairly large in the case of jet engines, caused airspeed to bleed off to such an extent that a significant forward movement of the throttles would occur just prior to landings. An alternative method is to program the throttles back at a fixed rate after flare initiation.."

Another constant airspeed control system commands a change in approach airspeed at a predetermined altitude. It was used for an experimental study conducted by the Air Force with a T-33 aircraft and was described as follows: (11)

> "The simplest form of airspeed control for landing was provided by changing airspeed command from an approach to a landing value at a predetermined height. This was accomplished by minor modifications to the automatic airspeed control, the addition of an extra airspeed reference controller, and the use of an altitude actuated landing speed sensor . . . . ."

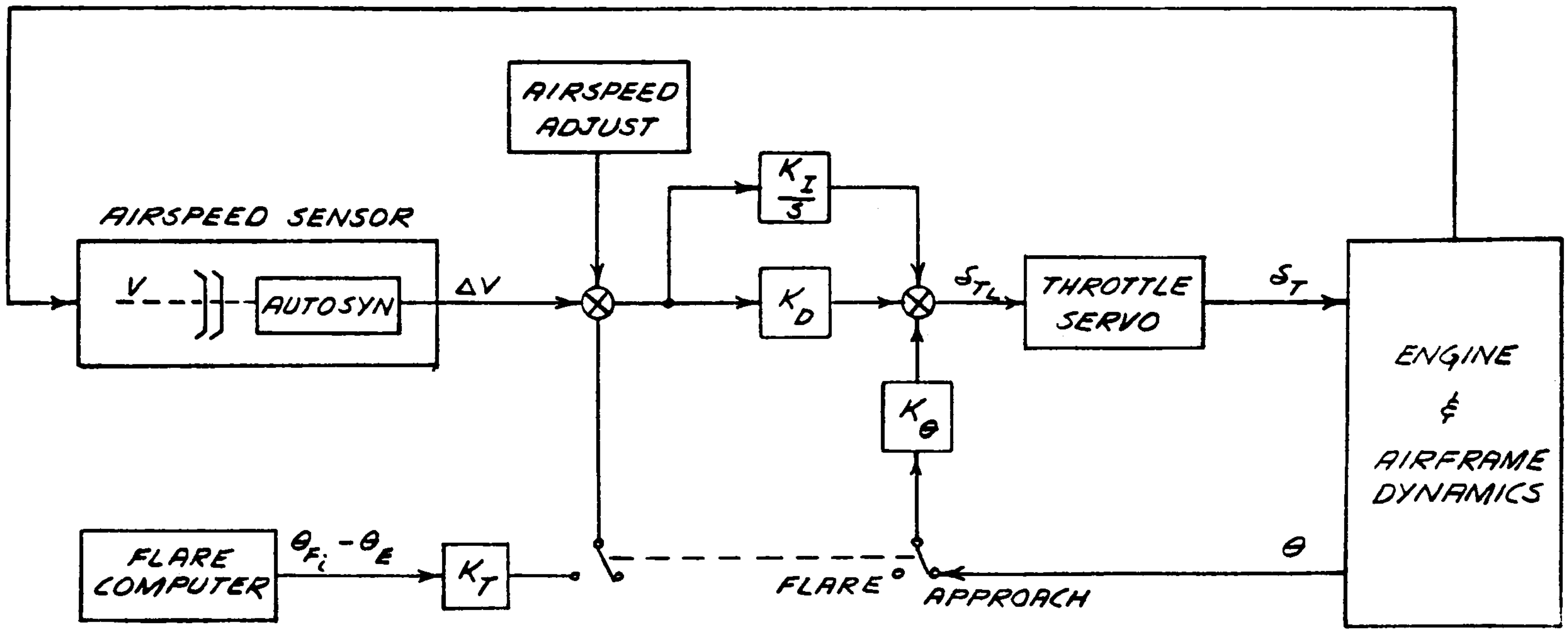


Fig. 31 *THROTTLE CONTROL SYSTEM*

(Taken from Reference 23)

"Fully automatic approach-landing airspeed control is not possible with the test configuration, since the human pilot must calculate the approach-landing airspeeds needed. His calculations are based upon such factors as gross weight, gusts, etc. After deciding upon the values for approach and landing airspeed, the pilot must manually set the two airspeed reference selectors to the desired airspeed command. This must, of course, be done before the commands are to be used. Sequencing and actual airspeed control is fully automatic."

Figure 32 is a block diagram of this automatic approach and landing airspeed control.

A.2.2 Pitch Attitude and Thrust Command Technique

This system is being evaluated by several airlines at present. The following description has been abstracted or paraphrased from Reference 13:

"This system is an integrated instrument system that provides both pitch and thrust guidance. By means of both pitch and thrust command, the system maintains the proper speeds and control for dynamic as well as static conditions during takeoff, approach, and go-around.

"There are two basic parameters that are combined by . . . (the system): angle of attack and forward acceleration. Each of these parameters provides anticipatory information for the other. Angle of attack change caused by pitch will anticipate change of acceleration. Acceleration change caused by thrust will anticipate change of angle of attack.

"The angle of attack, or lift, is sensed by a small vane located near the leading edge of the wing. The thrust is sensed by a pendulum which is oriented to the pitch gimbal of a vertical gyro. Flap, oleo, and power quadrant switches provide automatic mode selection. The combined signal is presented on the flight director pitch command bar for use during takeoff or go-around, and on a small null-reading meter mounted on the rim of the airspeed indicator for use during

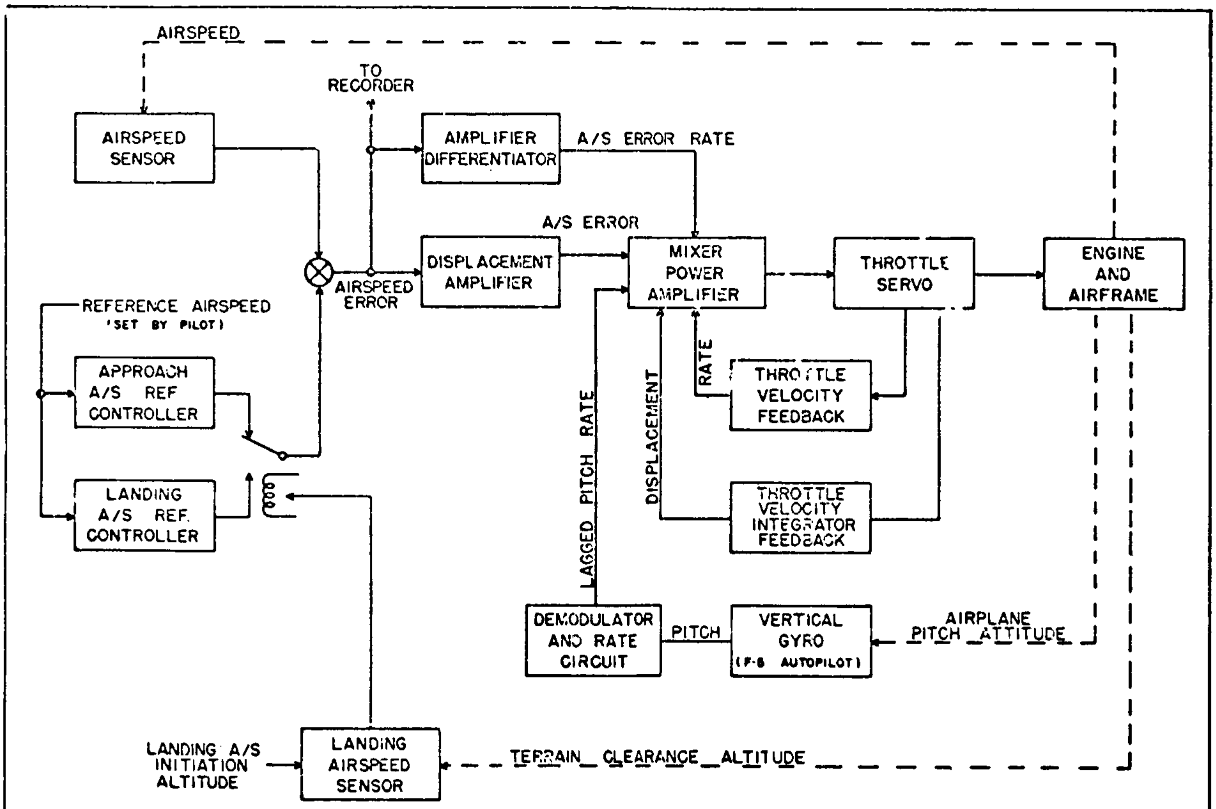


Fig. 32 **BLOCK DIAGRAM OF AUTOMATIC APPROACH AND LANDING AIRSPEED CONTROL**

(Taken from Reference 11)

approach. Automatic power control servo(s) may be operated on an open loop basis by amplifying the . . . (system) output signal.

"For engine out conditions . . . (the system) will command the V_2 speed certified for the aircraft. Modern jet transports have been certified with variable V_2 speeds which are a function of engine thrust, minimum control speed, weight, and flaps. All of these variables are sensed by the lift, flaps, pendulum, and pitch angle sensors and are combined to exactly match the certification V_2 and minimum control speed charts.

"During landing approach the flight director is relinquished to navigation requirements and the rim-mounted . . . (system) indicated is used for thrust command. The lift null is controlled by the flap position so as to maintain the proper speed schedules from initial area maneuvering until the landing flare. All changes in pitch angle are promptly solved by thrust command, which aligns the pendulum with its pitch reference. All excursions in speed or block changes in speed reference are led by the forward acceleration signal. The power is commanded smoothly and with a minimum of control excusion. Overly active power changes, whether manual or automatic, are intolerable for commercial transport applications.

"Should a steeper than normal descent rate occur during final approach, it is desirable that the speed be increased accordingly. This provides a reserve of kinetic energy in anticipation of the speed bleed off when the steep rate of descent is checked, thereby preventing a speed undershoot. When the descent is steeper than normal . . . (the system) utilizes a pitch angle biasing signal of three knots speed increase per degree of flight path gradient. Associated with steep descent during final approach is a low thrust low rpm condition where the engine acceleration response is poor. This extra speed allows sufficient time for the engine to accelerate evenly.

"For flight at minimum speeds, strong turbulence or maneuvering wing loading may cause a temporary excursion to an excessive angle of attack. To counter this possibility, the angle of attack signal is strengthened whenever it increases from list null more than a predetermined amount. This provides an increased command against an excessive maneuver rate during turns and rotations and also decreases the excursion toward stall when strong turbulence conditions exist.

". . .(the system) does not have any manually operated switches, mode selectors, or reference settings. The system automatically changes from takeoff speed schedules to landing speed schedules, and automatically compensates for weight changes, bank angles, and flap changes.

"Prior to landing approach, the . . .(system) signal is centered while at maneuvering flap position as a check on the accuracy and response of the system and a check on computed landing weight. Indicated airspeed will then change according to a precise schedule as flaps are extended to full down. Since the . . .(system) has been used during the final approach, the pilot is assured that the system is functioning at the moment that a go-around maneuver might be required.

". . .(the system) is conveniently monitored by independent reference systems because the . . .(system) pitch command is integrated with the flight director horizon display and the . . .(system) speed command is integrated with the indicated airspeed display. The flight director command bar and background horizon move in unison, calling immediate attention to any discrepancy. Accuracy and flyability of manual response to . . .(the system) thrust command is comparable to that achieved when the power schedulers are automatically coupled to . . .(the system) providing pilot back-up of automatic operation. The pilot may take over the power scheduler at any time during the approach and follow the command signal manually."

A. 2.3 Angle of Attack Control Technique

This system was developed primarily as an aid to the manual landing of jet aircraft on aircraft carriers. The following description was taken from reference 28:

"Angle of attack has been chosen as the parameter to be controlled in order to achieve the lowest landing approach speed consistent with a specified lift margin, in g units, or a specified value of V/V_S, independent of variation of gross weight of the airplane and independent of the bank angle on turns. Thus the airspeed automatically varies with gross weight and automatically increases on turns as required to maintain the optimum angle of attack. In this way a predetermined lift margin in terms of g units or V/V_S is maintained against the possibility of buffet or stall.

"Angle of attack is maintained constant at the preset value except for momentary excursions resulting from air turbulence or momentary excursions during rapid changes in pitch attitude. Airspeed variations resulting from wind shear are corrected quickly with a minimum of overshoot. There is no airspeed input to the system; but, in operation the airspeed is highly damped so that there is no tendency toward airspeed oscillation.

"The Autothrottle System consists essentially of a computer, two transducers, and a throttle actuator. There are only two inputs to the computer. They are angle of attack, obtained from an angle of attack transmitter, and normal acceleration, obtained from a very simple type of accelerometer. No airspeed transducers or gyroscopic devices are used. The system may be engaged at any airspeed permitted in the landing configuration, while flying level, turning, climbing or descending. The computer determines the proper throttle position to adjust angle of attack to the preset value. It varies the thrust in accordance with variation in flight path angle and in accordance with variation of total aerodynamic drag which is a nonlinear function of angle of attack. It also considers the lag in engine response. An integrating error-correcting feature is provided to completely correct any angle of attack error which might otherwise persist.

"This autothrottle system has wave-off capability. Wave-off is accomplished by adjusting the pitch attitude of the airplane as required to position the throttles for maximum available or maximum permissible thrust. The result is a stable flight path at the steepest angle possible for the existing conditions of gross weight and thrust, independent of engine malfunction."

A.3. APPROACH LATERAL GUIDANCE

Approach lateral guidance is a method for controlling the position of an aircraft in a horizontal plane from the point of acquisition during initial approach until touchdown. This control is maintained relative to the extended runway centerline referred to as the localizer path.

A.3.1 ILS Localizer Coupling Technique

Since the Instrument Landing System is the most frequently cited method for approach lateral guidance, a brief discussion of this technique, abstracted from reference 26, is presented here.

The ILS localizer transmitter operates in the 108 to 112 nc frequency band and is physically located beyond the departure end and on the center line of the instrumented runway. It is generally oriented to provide a single fixed path azimuth angle for guidance along the centerline of the runway. The ground based localizer antenna is actually composed of several (usually 5 to 8) properly spaced, horizontally polarized individual antennas. The individual antennas are excited with an RF carrier and 90 or 150 cycle carrier modulated side band components whose amplitude and phase relationship is carefully adjusted to produce the desired directional pattern. The patterns are such that the 90 cycle component is in phase and the 150 cycle component is out of phase with the carrier modulated components to the left of the runway centerline as viewed from the runway. The relationships are reversed on the other side of the runway. Accordingly, an angular LOP guidance system is formed.

The ILS localizer guidance technique can be viewed as a closed loop guidance system. The ILS receiver detects the aircraft's deviation from the localizer path and feeds this error signal to the autopilot coupler where it is appropriately shaped and then introduced as a bank command to the aircraft's autopilot. For all practical purposes with regard to the ILS performance, it can be assumed that the aircraft performs coordinated turn maneuvers. In general the turn coordination is enforced by the autopilot, which senses the side slip angle and drives it to zero. The aircraft responds with a change of its flight path which in turn will be perceived by the receiver as a change of the localizer error signal.

Generally it is anticipated that improvements can be made in the ILS localizer systems to permit vertical guidance by these systems down to touchdown and perhaps even for initial roll-out guidance. These improvements are primarily directed toward development of a directional localizer wave guide type of antenna. The wave guide antenna produces a localizer course of standard coarse sensitivity but almost all of its energy is confined to a zone ± 10 degrees from the approach centerline. This narrow pattern eliminates the bends that are sometimes present in less sophisticated localizers from reflections.

Using the side-slip technique for returning aircraft to the centerline after deviation from the localizer beam, the aircraft may no longer fly on a curved path but returns to the localizer course in a slip. Before he starts the approach the pilot presets the heading of the runway on his flight director which, in the event of deviation of the aircraft from the localizer beam, gives the necessary signals to the autopilot. These signals cause the aircraft to bank (for reasons of safety the bank angle is limited to between 3 and 5 degrees), but the rudder will displace to keep the aircraft from turning so that the aircraft is unable to turn about its yaw axis and skids back toward the beam. This method of lateral localizer control has already been tested and has yielded satisfactory results. Return to the localizer beam may be effected more quickly than by other methods, and, since the aircraft is constantly in line with the runway, there is no need for drift compensation.

A.3.2 Precision Tracking Radar Technique

Approach lateral guidance provided with a precision tracking radar system is essentially the same in concept as final approach vertical guidance discussed in Section A.4. Briefly, the aircraft's lateral position as determined by the radar is fed into a lateral control computer. This computer compares the actual aircraft position with the desired position (following runway centerline) and an appropriate error signal is generated in the form of a bank angle command. The bank command is transmitted to the aircraft via data link.

A.3.3 Scanning Beam Transmitter Technique

Lateral guidance control with the scanning beam transmitter can be accomplished in a manner similar to that described for final approach vertical guidance in Section A.4.4. Briefly, the ground system would transmit a continuous series of coded angular azimuth data which would be received and decoded by the aircraft and utilized for introduction into the autopilot coupler.

A.3.4 Leader Cables

A magnetic leader cable system for final approach lateral guidance has been developed giving lateral accuracy of about 5 feet. The ground equipment consists of two cables laid on either side of the runway at a distance of about 250 feet from the centerline and extending from 5000 feet beyond the runway threshold in the undershoot area to as far along the runway as azimuth guidance is required during ground roll-out. The cables are fed with an alternator with an electronic control to stabilize the current in each cable. The servicability state of this equipment is indicated in air traffic control by a remote monitoring circuit similar to that of the ILS equipment.

The airborne equipment consists of a rotating loop aerial which must be outside the aircraft's metallic skin in a simple three-valve receiver whose output is low level dc current similar to that of the ILS system.

When the aircraft is at a height of about 300 feet it enters the coverage of the leader cable system and azimuth control is switched from the localizer to leader cable.

A.3.5 Doppler Beacons

Twin Doppler beacons have also been proposed for precision azimuth guidance. With the use of the Doppler technique, bearing indications are characterized not by modulation amplitudes but by phase or frequency shifts which have a high degree of insensitivity to irregularities in the carrier frequency. Two directional antennas emit both a reference signal (similar to that generated by frequency modulation in the VOR) and two modulation frequencies, one phase being 45° in advance of the reference phase and the other 45° behind. The aerial radiation pattern exhibits a number of identical phase geometrical positions (isophases) which run roughly parallel to the base line. For instance, if two beacons are erected one on each side of the runway, a phase angle deviation of one degree would correspond to a distance of about 13 feet from the guide line. This is moreover independent of the distance of the receiver. By comparison of the dipole patterns and the frequency employed, bearing indications can be received by normal VOR airborne equipment and processed without the need for auxiliary equipment.

A.3.6 Low Frequency Transmitting Stations

In this system, two small transmitting stations, sited at each side of the threshold of the landing runway, emit low-frequency signals which define a plane standing vertically on the runway axis. By comparing the phases of these two transmissions it is calculated that a lateral accuracy of better than one foot could be obtained at the runway threshold. The system can be adapted to give guidance information not only during approach but also throughout the ground roll along the runway.

A.4 APPROACH VERTICAL GUIDANCE

Approach vertical guidance is a method for controlling the position of an aircraft in a vertical plane from the beginning of final approach (a point equivalent to glide slope engagement) through an extended approach segment to the initiation of flareout. This control is necessary to maintain the aircraft on a desired or optimum straight line vertical flight path referred to as the glide slope.

A.4.1 ILS Glide Slope Coupling Technique

Since the ILS glide slope is one of the most frequently cited methods for final approach vertical guidance, a brief discussion of the technique, abstracted from reference 26, is presented here.

The ILS glide slope transmitting facility operates in the 329.3-335 mc frequency band and is generally oriented to provide a fixed single glide path angle of approximately 2.5 to 3 degrees. The transmitter is located near but to one side of the desired touchdown point of the instrumented runway. This distance is usually between 750 and 1250 feet from the approach end of the runway.

The null-reference glide slope antenna system is in general use today. It employs two antennas mounted on a vertical mast. The shape of the glide slope depends on both the RF energy radiated directly from the antenna and that which is reflected from the earth. Irregularities will appear in the glide slope if the terrain surrounding the antenna is not reasonably level or if the ground beyond the runway is rising. Consequently, surface undulations will produce a roughness in the glide path. In addition, signal reflections from hills and other structures produce an alternating fly up and fly down signal called path scalloping.

The ILS glide slope vertical guidance technique can be viewed as a closed loop guidance system as shown in Figure 33. The ILS receiver detects the aircraft's deviation from the glide slope and feeds this error signal to the coupler where it is appropriately shaped and then

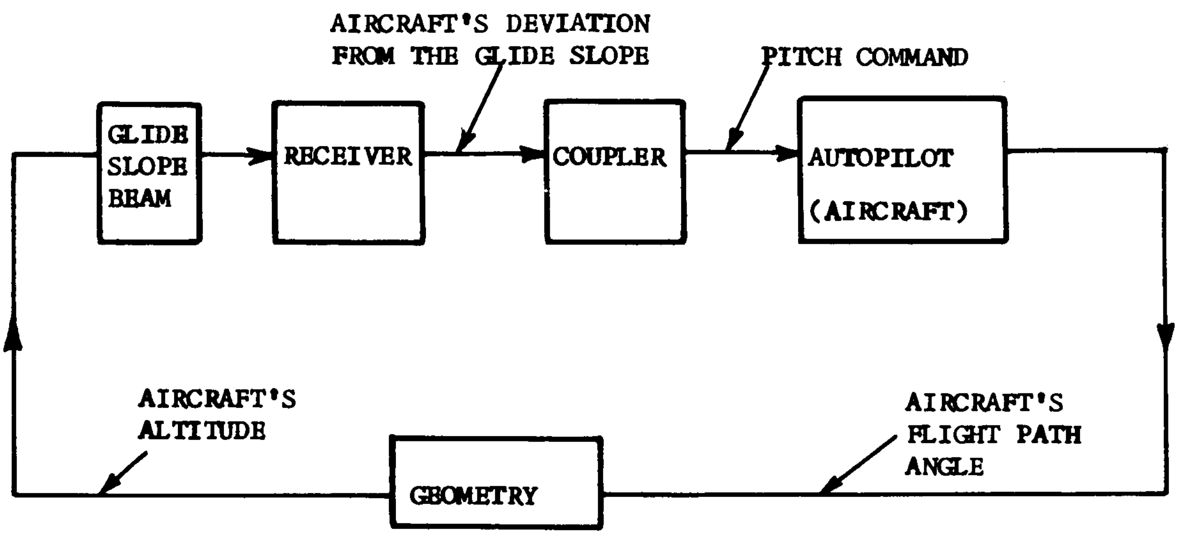


Fig. 33 ILS GUIDANCE LOOP

introduced as a pitch command to the aircraft's autopilot. The aircraft responds with a change of its flight path angle which in turn will be received by the receiver as a change in the glide slope error signal.

The ILS glide slope receiver selectively filters the detected modulation components of the signal to form separate 90 and 150 cycle signals. The 90 and 150 cycle frequencies are rectified and added to and subtracted from one another. The DC signal that is the difference between the magnitudes of the two components is an analog voltage whose polarity is indicative of displacement direction and whose magnitude is proportional to the degree of displacement of the aircraft from the established path. This signal is introduced into the autopilot coupler for automatic final approach vertical guidance.

As mentioned earlier, the glide slope beam is too unstable to be used below altitudes on the order of 100 to 200 feet. Another method of vertical guidance or an augmented glide slope guidance circuit must be employed for vertical guidance in this region.

A.4.2 Glide Slope Extension Techniques

Vertical guidance from initial acquisition of the ILS glide slope beam to a point where the aircraft reaches a predetermined altitude (probably between 200 and 100 feet) is essentially a normal autopilot coupled ILS approach except for improved precision of the airborne equipment in the ground based ILS system designed to all-weather Category III standards. As the aircraft reaches the middle marker (200 feet altitude) or some lower predetermined altitude (100 feet) the system is operating in the glide path extension mode. In this mode a vertical velocity sensor (VVS) is used to smooth out any roughness in the glide slope beam until flareout altitude is reached. Pitch attitude is maintained at the average pitch attitude the aircraft assumed while flying down the glide slope. This average pitch attitude is maintained for a few seconds until the flareout altitude is reached.

The vertical velocity sensor may contain both inertial and barometric sensing devices to measure the airplane's average rate of descent prior to the middle marker (or beginning of glide slope extension) where the glide slope beam is relatively free of perturbations. This measured rate of descent prior to the middle marker generates a signal which subsequently is used to override ripples in the glide slope beam maintaining the aircraft at the same average rate of descent until flareout is initiated. This type of device can be accurate to within one foot per second and have a time constant less than 0.1 seconds. Two types of vertical velocity sensing techniques are described below.

A.4.2.1 Inertial Rate of Descent Sensing (IRODS) Technique

The glide slope signal provides the pitch control in the automatic mode until the aircraft reaches an altitude of 400 feet. At 400 feet, washed out pitch rate and altitude rate signals from a landing computer are added to the autopilot ILS glide slope coupler. During the 400 to 200 foot interval, a landing system integrator follows the pitch attitude and glide slope error signals. The flare integrator in the landing computer establishes an average sink rate from 1000 to 200 feet. At 200 feet the hold sink rate mode is initiated, using the sink rate average established by the landing computer flare integrator. The pitch attitude and glide slope signals are removed from the autopilot and replaced by the output of the landing system integrator. To provide an altitude rate that is relatively noise-free, an inertial rate of descent sensor (IRODS) is used. The IRODS concept provides an inertial smoothing of the radar altimeter sinking rate. This is accomplished by integrating the vertical acceleration obtained from a linear accelerometer. The integrated output of the linear accelerometer is compared with the altitude-rate output of the radar altimeter, or a barometric altitude rate signal. The resultant error signal is passed through a lag network and is used to correct any bias or drift that may be present.

If the approach terrain to an airport is either rolling or sloping, barometric altitude rate must be used to supervise the IRODS to an altitude of approximately 100 feet. At this altitude the terrain, in most cases, will be level relative to the runway. This will allow the use of radar altimeter altitude rate.

From 200 to 100 feet the proportional and integral signals from the landing computer control the aircraft. At 100 feet the output of the terminal control portion of the landing computer is switched into the flare integrator and the flare computation is initiated.

The preceding mode sequence provides for very stable glide slope control below 400 feet. At 200 feet all the landing system equipment is in operation, with the exception of two parallel relays which, at 100 feet, control signals to the flare integrator, giving the pilot an opportunity to observe system operation.

From 200 to 100 feet, during the hold altitude rate mode, the pilot monitors the glide slope error on the attitude director indicator (ADI) to check the spacial position of the aircraft. At the 100 foot altitude point the ILS glide path signals are switched off and the flare computer takes over pitch control.

A.4.2.2 Instantaneous Vertical Velocity Sensing Technique

This technique is based upon an instantaneous vertical velocity sensor (IVVS). It uses a barometric rate of descent sensor to obtain a steady state inference signal. At the same time a vertical accelerometer, the output of which is integrated, provides an instantaneous vertical velocity signal. Using these two signals a signal proportional to altitude rate of change is obtained. In this way the effect of lags in the barometric sensor is eliminated and the system is not dependent on radio altimeter information.

The value ascertained in this manner is used to control the pitch axis of the autopilot during glide slope approach and flareout. At the instant of initial engagement with the glide slope beam a rate of descent signal representative of that found in the typical glide slope approach is introduced into the pitch axis control. If the aircraft moves off the centerline of the glide slope path the rate of descent commanded by the autopilot is automatically changed until the aircraft remains centered at constant rate of descent on the glide slope beam. In this way the function of the glide slope beam signal is limited to that of monitoring the approach and the beam ceases to act as a primary source of data for the control of the aircraft's pitch. Thus the basic parameter for aircraft vertical guidance is rate of descent.

A.4.3 PRECISION TRACKING RADAR TECHNIQUE

After lock on the aircraft is continually tracked by the radar, and a set of rectangular coordinates consisting of range, altitude, and lateral displacement are found in the position computer relative to the radar gimbal axes. These coordinate data are then fed into a vertical control loop computer which compares the actual aircraft position with the desired position (pre-selected approach angle) and an appropriate error signal in the form of a pitch command is generated. The pitch command is a function of both desired altitude and sink rate. The pitch command is transmitted to the aircraft via data link, and introduced into the autopilot coupler.

There are basically two types of data link used with the system. One is the normal ILAS system; the other is a beacon-receiver-transponder system. When the ILAS data link is used, the control information is converted to an equivalent beam signal and transmitted to the aircraft on specified localizer and glide slope radio signal frequencies. The radar beacon data link utilizes the K_a-band radar beam to transmit guidance data to the aircraft. In the airborne equipment, the transmitted electronic signals are received, decoded, and supplied to the autopilot and/or cross-pointer needles. With either data link, the basic operation of the system is the same.

A.4.4 SCANNING BEAM VERTICAL GUIDANCE TECHNIQUE

Vertical guidance provided by scanning beam transmitters on the ground has not been fully implemented. These types of systems have primarily been used in conjunction with ILS to provide more accurate flareout guidance. The scanning beam type of system is, however, feasible for vertical guidance during approach and flareout.

Two basic types of scanning beam transmitter systems for vertical guidance are under development today. One technique may be identified as the Biangular technique and the other as the Range-Angle technique. The basic concept of these two techniques has been discussed as a method of automatic flight control in Sections 4.3.3.1 and 4.3.3.2.

When the glide path function is engaged, a rate-of-descent command is introduced into the pitch axis of the autopilot; this command is adjusted to approximate the rate of descent which could be expected at average airplane speed and beam angle. Before introduction into the pitch axis, the command signal passes through a potentiometer on the output shaft of a radio altimeter in the servo positioning loop.

This potentiometer is blanked out so that a maximum signal is obtained at all altitudes above 50 feet; hence engagement of the glide slope function itself is a test of the entire flare system. If the radio altimeter is inoperative, no pitch-down signal will be obtained at the time of glide path engagement. If a failure has taken place in the command signal string through the radio altimeter potentiometer, again no pitch-down signal will be obtained on engagement. If at any time during approach the descent command signal should fail, the aircraft will level out and maintain zero rate-of-descent flight.

This feature indicates to the pilot that his flare system is operative from time of glide path engagement to initiation of flare without the need for other tests or monitoring.

The integral of the glide slope error signal is used to modify the commanded rate of descent so that the aircraft will follow the center of the beam. Thus, if after engagement the resulting rate of descent is insufficient to keep the airplane on the center of the beam, the resulting beam error will cause the rate-of-descent command to increase until the center of the beam is maintained.

The glide path beam error signal is modified by a separate potentiometer on the radio altimeter servo positioning shaft; the potentiometer is designed so that a maximum glide path signal is obtained at all altitudes above 250 feet (this altitude is not critical). At this time, the radio altimeter will command linear decrease in gain of the error signal until a 50-foot altitude is reached at which time the signal becomes zero and flare is initiated. Because of the extremely tight glide path control obtained with the rate-of-descent signal, there is no requirement for scheduling flight path gain from the moment of engagement at the outer marker until the fade-out of the glide path begins at about a 250-foot altitude. Inasmuch as the glide path error signal in the rate-of-descent command loop decreases from the 250-foot point to initiation of flare, correction is obtained for wind shifts which take place between 250- and 50-foot altitudes.

A.5 FLAREOUT

Flareout is a maneuver for changing the aircraft attitude and reducing the rate of descent just prior to touchdown in order for the aircraft to establish a desirable angle of attack for runway contact with the main landing gear and to touchdown at an optimum rate of descent. Flareout is usually initiated when the aircraft is in the vicinity of the runway threshold and results in a gradual change in attitude and rate of descent until touchdown.

The three primary types of flareout maneuvers being considered for automatic control are illustrated in Figure 34. These are known as "fixed path", "exponential path" or "parallel path", and "terminal path" and have been described in reference 9 as follows:

"a. Fixed path controllers fly a fixed path with respect to the ground. The shape of the path is arbitrary - exponential, circular arc, straight line segmented, etc., or a combination of such elements. As some latitude in the touchdown point is permissible, and in fact desirable, in order to avoid excessive control and maneuvering activity, fixed paths were deemed to be unduly restrictive for landing guidance and were not considered further.

"b. Parallel path controllers also fly some arbitrarily shaped path which, however, is one of a family of such paths satisfying the control law. The effect of disturbances is to displace the aircraft from one path to another within the family. The simplest controller of this type is that employing an exponential path as it merely requires that the altitude rate be proportional to the altitude throughout the flare. This controller, hereafter referred to as the exponential controller, was chosen for further study.

"c. Pure terminal condition controllers fly paths, of which the desired terminal conditions are preset as control references during the flare. Any error between these desired conditions and continuously predicted conditions at the terminal point is converted into control

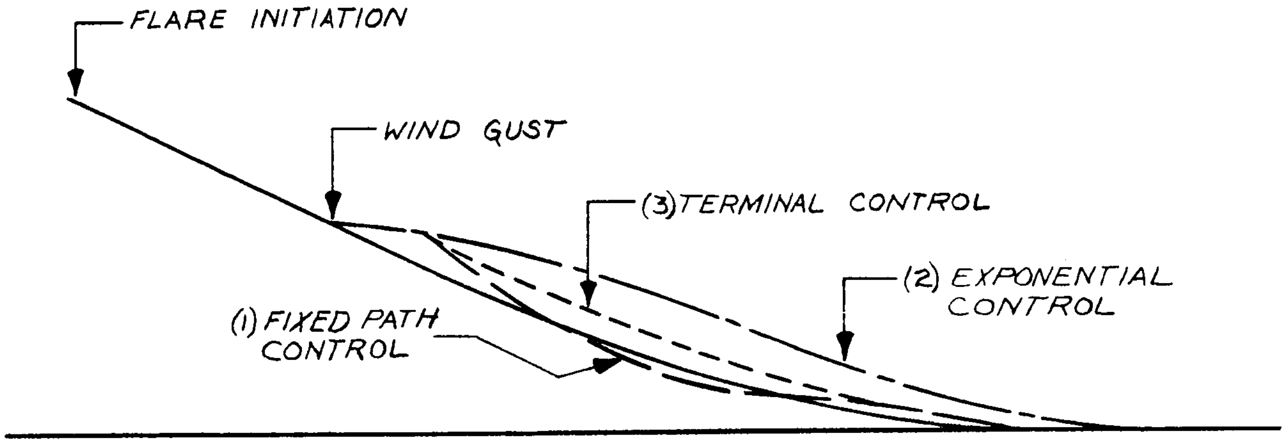


Fig. 34 Flare Maneuver Control Techniques

action to minimize the error. A pure terminal computer is here defined as one which follows this form of control, without modification, to the terminal point. For example, changes in control philosophy near the terminal point, such that the predictions are stopped or the number of controlled variables is changed, are considered modifications to the pure terminal controller. Although the characteristics of the path depend on the particular type of terminal control used, in principle each terminal controller is capable of flying a greater variety of paths than would be possible under a parallel control method."

A.5.1 Exponential Path Controller, Radio Altimeter Initiate and Control Technique

The most frequently cited flareout control technique entails Radio Altimeter initiation and control of rate of descent and an exponential flare path controller. This technique has been initially discussed in a recent WADC report (31) as follows:

"We will assume that the aircraft is equipped with an automatic pilot and an automatic approach coupler, in addition to the other equipment which we will find necessary to accomplish automatic landings.

"The automatic approach coupler is the device which receives signals from the I.L.A.S. receivers in the aircraft and transmits these signals, in a suitable form, as commands to the automatic pilot, during an automatic approach. This equipment is, of course, an integral part of the automatic approach system. It is logical, then, for the automatic flareout system to employ this same equipment.

"Since an exponential path for the flareout requires that the rate of descent be adjusted as a function of absolute height, a radio altimeter of high accuracy is required.

"Height information from the altimeter will then be furnished to a so-called flareout computer. If the aircraft is not following the correct exponential path, the flareout computer will send an error signal to the pitch channel of the automatic approach coupler, which will, in turn, cause the automatic pilot to change the pitch attitude of the aircraft. This new pitch attitude will cause the aircraft to assume a new rate of descent, tending to correct the error from the desired exponential path.

"This rudimentary automatic flareout system is shown in block diagram form in Figure [35].

"The basic automatic flareout system which we have just described depends entirely on the existence of a displacement from the desired path for control action. It follows that the aircraft can never fly the correct path with this system because a more positive control action is required to flare.

"This deficiency is particularly noted at the beginning of the exponential path, because at that time the curvature of the flight path should be a maximum. The system will not begin to move the elevator surfaces until an error exists; as a result, the aircraft will contact the runway before the rate of descent has been significantly reduced.

"In addition to the serious shortcomings we have already mentioned, another bad feature of the basic flareout system must be recognized. That is, our basic system attempts to control both rate of descent and pitch attitude by elevator motion alone.

"If we are considering only very short time intervals, the elevator can be considered to be the airplane's rate of descent control. We must realize, however, that once the transient response to an elevator motion has subsided, the rate of descent will depend only on engine power, since the engine is the airplane's primary rate of descent control. This can be seen by considering only the basic physics involved:

"The rate at which the aircraft is using energy depends upon its drag, speed, and rate of climb, since the latter represents the rate at which the potential energy of the aircraft is increasing or decreasing. This required power can only come from the engine;

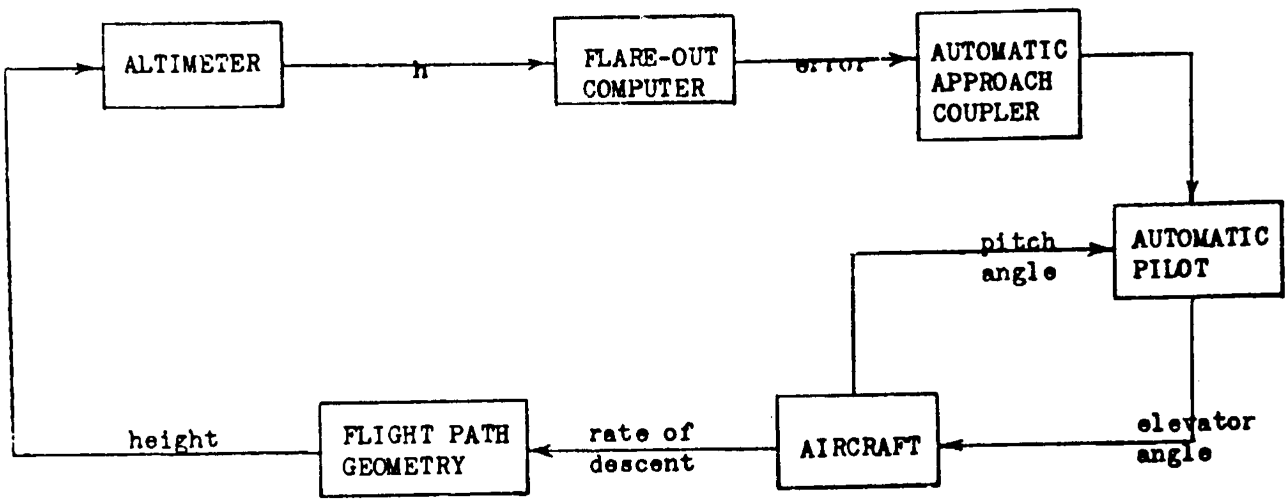


Fig. 35 Block Diagram of the Basic Automatic Flareout System

(Taken from Reference 31)

control of rate of descent by elevator motion alone must be considered to be incomplete and unsatisfactory."

Solutions to the problems presented above were discussed in the report and then a brief description of a complete automatic flareout system was presented:

"A block diagram of a complete automatic flareout system is shown in Figure [36]. This system begins with the basic flareout system (altimeter - computer - approach coupler - automatic pilot - airplane) and may incorporate one or, perhaps, all three of the stabilizing control devices we have mentioned (smoothing time constant, notch network, and pitch rate signal).

"In addition, a pitch reference voltage is utilized to eliminate the steady displacement error and to provide a more positive type of control.

"An automatic airspeed control provides the needed changes in engine power to fly the required path safely, and an automatic runway heading control is available to remove any crab angle resulting from a cross wind.

"We have concluded on the basis of our simulator studies, that a fully successful automatic flareout system must incorporate these essential items. We will see in the remaining portion of this paper that this conclusion has been verified by actual flight test experience."

A.5.2 Radio Altimeter Initiation and Control Techniques

Flareout is initiated when the radio altimeter indicates the aircraft has reached the required altitude. This flareout altitude value is adjustable, however, it will occur at an altitude of approximately 50 feet. At this point the aircraft should be over the smooth runway surface and any irregularity beyond the runway threshold, which is a disadvantage of the radio altimeter, would not be of concern. When flareout is initiated the flare computer provides the vertical guidance commands

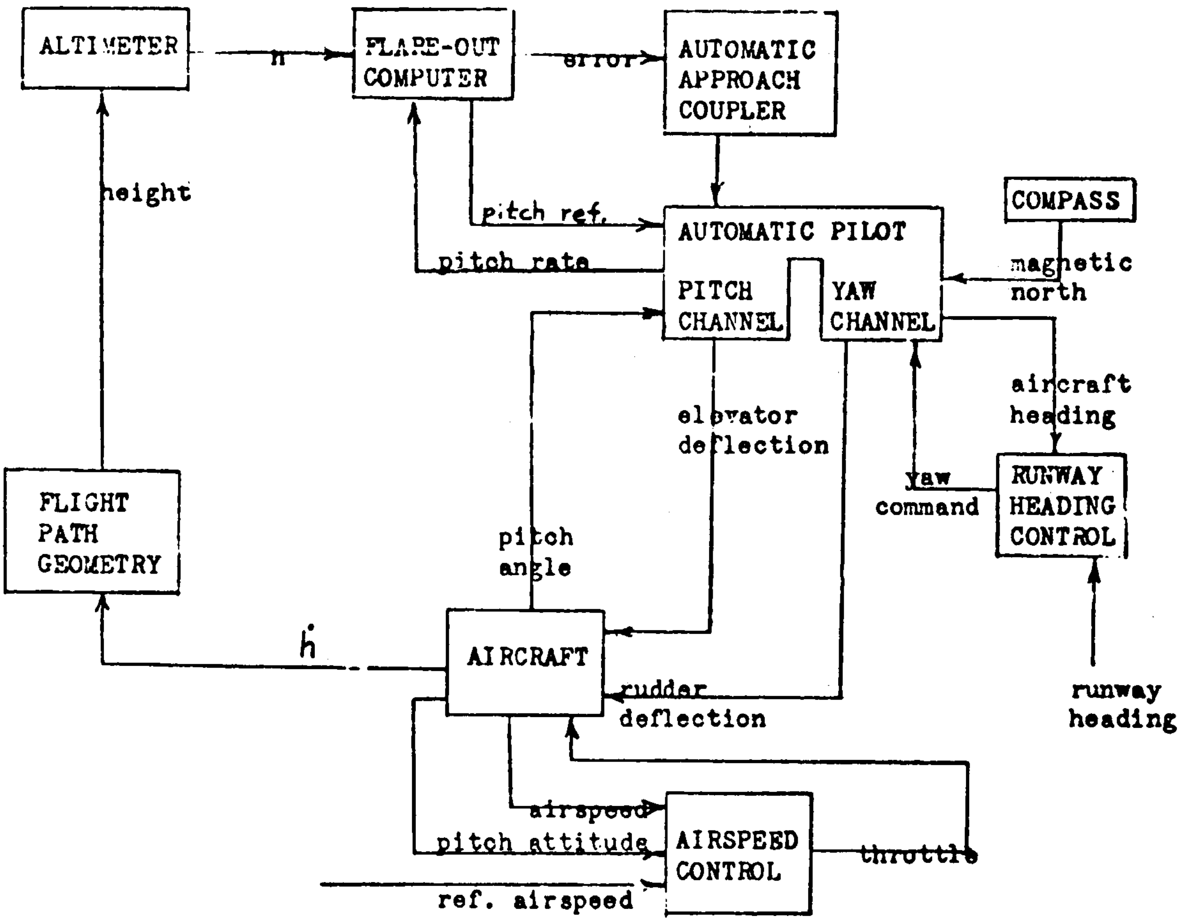


Fig. 36. Block Diagram of Complete Automatic Flareout System

(Taken from Reference 31)

to the autopilot from this point until touchdown. The flare computer provides a continuously exponential flare pattern from initiation (for example from 50 feet at a sink rate of approximately 10 feet per second) to a touchdown at a sink rate of 2 feet per second. In other words, the lower the aircraft the more slowly it sinks. If any wind gusts or perturbations occur these are integrated by the computer and a continuously smooth rate of descent is recomputed to provide the desired touchdown at 2 feet per second.

This general technique is described in Reference 8 as follows:

". . . radio altimeters will have to be used as an altitude reference during flare. Therefore, at some point during or prior to the flare, the barometric rate of descent component of the augmented rate signal must be replaced by the ground referenced rate of descent signal. For reasons of safety and pilot confidence, this replacement is accomplished prior to flare initiation but at an altitude below 200 feet. The effect of a 1 ft/second misalignment of the two references was found to be less than 50μa at an altitude of 50 feet.

"Flight tests have shown that the radar altimeter is relatively noise-free and that a good rate signal can be derived from it. It might therefore be argued that inertial augmentation is not necessary, thus avoiding the switchover problem. If landings were to be made only at selected sites where the terrain at the approach end of the runway is relatively flat, this might indeed be sufficient. General operational requirements, however, dictate that the radar altimeter rate signal cannot be relied upon until the airplane is essentially over the runway. Therefore, switching will probably have to take place between altitudes of 200 and 60 feet. An altitude of 100 feet is being used as a nominal value.

"The exponential flare control function consists of an altitude rate command which is proportional to actual altitude. The altitude reference is biased so that at zero altitude a positive sink rate will be commanded thereby reducing the tendency toward large longitudinal dispersions. The control function may be written as:

$$\dot{h}_c = \frac{1}{\tau}(h-H)$$

where H = altitude bias in feet

τ = flare path time constant in seconds

"The altitude rate signal, $\dot{h}$, is derived from a radio altimeter which replaces the barometric altitude rate signal to the augmentation circuit by switching at an altitude of approximately 100 feet. An altitude rate error is generated by comparing the command with the actual altitude rate. The pitch command to the autopilot is then made proportional to the altitude rate error and integral of altitude rate error. . . .

"In order to avoid transients at the beginning of the flare, the flare control function is switched in by a null sensor when the altitude rate error is zero.

" . . . As the aircraft descends on the glide slope the flare altitude rate command decreases in value and approaches the actual value of altitude rate. At some point, which depends on the gain parameters τ, the flare curvature, and H, the flare altitude bias, as well as the aircraft rate of descent on the glide slope, a null occurs. If the aircraft were to continue the descent on the glide slope, the altitude rate error signal would again increase, but with the opposite polarity. The flare computer operates in such a way as to maintain the null when that mode is engaged."

A.5.3 Radio Altitude Initiation and Instantaneous Vertical Velocity Sensor Control Technique

In this technique, flareout will be accomplished using the same computer as the one used for glide slope control, the object being to give assurance that the system is working properly before the aircraft reaches the flareout altitude. The basic parameter of longitudinal control from the beginning of the glide slope to touchdown is rate of descent. The control signal is provided by an instantaneous vertical velocity sensor (IVVS) which uses barometric rate of descent and the integrated output of a vertical accelerometer to provide an altitude rate signal. At approximately 50 feet a radio altimeter commands initiation of flareout. Rate of descent is then commanded as an exponential flare maneuver terminating in a touchdown rate of approximately 2 feet/second. In this method the radio altimeter is not called on for direct pitch axis control but only to determine initiation of flareout maneuver. The pilot is aware of whether his flare system is operative from the time of glide path engagement.

A.5.4 Time-To-Go Initiation Technique

The flareout is an exponential path continuously controlled to result in touchdown at a sink rate of 2 feet per second.

The flare nose rotation command is approximately equal in magnitude but of opposite sense to the glide slope command. The flare command is transmitted to the aircraft as a slowly advanced pitch command at 14 seconds from touchdown. The altitude command begins to conform to a flare pattern 2 second later.

The altitude-command computer generates a signal that represents the desired altitude as a function of range, (fixed path) airplane speed, the commanded glide slope, and the airplane initial altitude. During the time interval between lock on and 12 seconds to touchdown, the altitude command is linear and is commanding a constant descent rate. Twelve seconds before touchdown, the altitude command smoothly decreases in such a way as to cause the descent rate of the aircraft to decrease to approximately 2 feet per second at touchdown.

The touchdown pitch attitude limits for the particular aircraft are considered for the flareout maneuver. If the aircraft maintains constant airspeed during approach and flare, the system commands the aircraft to essentially level flight during flare and an airspeed compensator will produce additional pitch commands to maintain lift.

A.5.5 Radar Altimeter Initiated Terminal Flare Technique

At 100 feet altitude, as determined by the radar altimeter, the glide slope command is switched off and the flare computer takes over pitch control. (The actual altitude at which the flare control is started will vary with the approach angle; however, for a normal 2.75 degree ILS approach the flare will start at about 100 feet above the runway altitude). The aircraft under control of the flare computer will fly a terminal control flare maneuver suitable to the aircraft dynamics. The flare path is computed to cause the aircraft to touchdown at a sink rate of 2 feet/second close to a pre-determined point. The output of the flare computer is continually smoothed by integrated data from an inertial rate of descent sensor. This consists of a closed-loop system in which an integrating accelerometer or velocity meter output is slaved to altitude rate derived from a radar altimeter. In order to minimize the effects of spurious accelerations due to aircraft maneuvers, the velocity meter is mounted on a two-gimbal platform. The platform is slaved to a roll-pitch attitude gyro which maintains the platform locally level. Thus, the velocity meter sensitive axis is maintained vertical in spite of roll and pitch motions of the aircraft.

A.5.6 Bi-Angular Flareout Technique

The bi-angular flareout technique, as explained under "Vertical Guidance", requires the use of two scanning beam transmitters located some 2500 feet apart on the runway. The antenna closest to the runway threshold is for glide slope, final approach vertical guidance and the antenna behind the glide slope antenna is for initiation and control of flareout. Conceptually, both antennas could radiate a family of elevation angles to allow selection of any glide slope approach angle and any flareout initiate angle. If this type of system is used with existing ILS installations, the ILS glide slope angle is, of course, a fixed angle but the flareout initiate and control angular transmissions are continually radiated between zero and 20 degrees. The flareout initiate point can be pre-selected for a given altitude represented by the intersection of the glide slope and flare beam as shown in Figure 37.

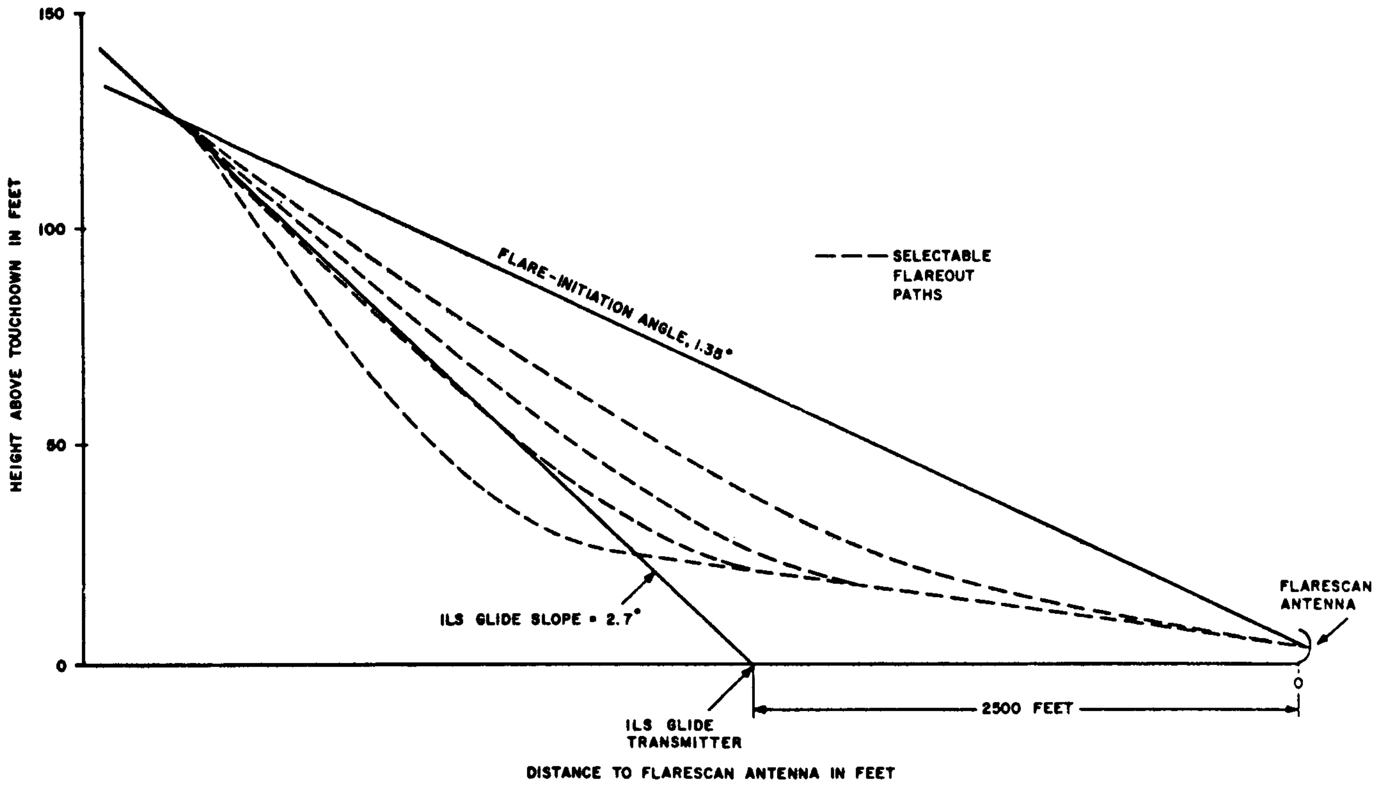


Fig. 37 Selectable Flareout Paths Using Biangular Technique

At the instant of guidance mode transition, the inputs to the autopilot coupler, formally the glide slope error signal, become an angular error signal derived from the flareout transmitter beam. The input to the coupler is still angle deviation error signal but instead of glide slope the error signal is the deviation of the flare transmitter angle from a time programmed reference value which, if followed, accomplishes a flareout maneuver to runway contact. The angle relative to the flareout angle can be varied (so that an exponential or other geometric flare path is commanded) by comparing angle, angle rate, and time to touchdown. This concept of angle versus time (representing distance) is shown in Figure 38. For a typical flareout maneuver the aircraft is commanded to fly along the pre-selected flareout path to a pre-selected elevation angle at touchdown (terminal angle).

The method just described is a selectable fixed path control method. The sink rate on the shallow terminal glide is between 1 and 2 feet per second (depending upon the landing speed) and runway contact is made when the height from the airborne antenna to the bottom of the landing gear subtends the value of the terminal angle. For typical airborne antenna installations (antenna height between 15 and 20 feet), runway contact is made at about half way between the glide slope reference point and the flareout beam reference point or about 1000 feet past the glide slope reference point.

A.5.7 Range-Angle Exponential Flare Technique

The range-angle technique for vertical guidance and flareout continually supplies the aircraft with angular elevation and range data. Altitude is easily derived from the range-angle data. This system can be used for complete final approach, vertical guidance and flareout, but has generally been used as a supplement to existing ILS glide slope beam. At some time after glide slope intercept, the range-angle system is engaged and pitch commands to the autopilot are provided by the landing computer until flareout in initiated.

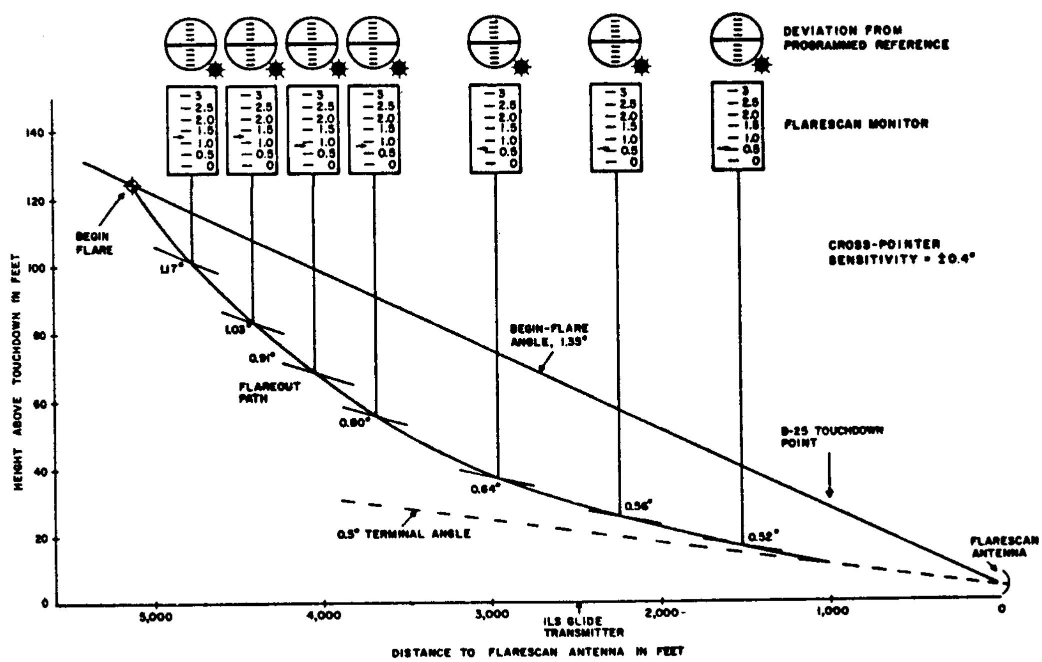


Fig. 38 Rotation to Terminal Flare Path Angle Using Biangular Technique

Flare is begun at a pre-selected altitude. The flare computer is of the exponential type and uses altitude and rate of descent data generated from the derived altitude. The rate of descent signal is augmented, on a high frequency basis, by the integrated, washed-out, normal accelerometer signal since the derived sink rate must be filtered to eliminate noise. It is emphasized that no radar altimeter is used in this system during the flare nor is barometric altitude required during approach. The output of the exponential flare computer presents the pitch command to the autopilot. The basic geometry of this technique is illustrated in Figure 39.

A.6 DECRAB

The basic requirement of the decrab function is to remove any angular difference between the heading of the aircraft along its longitudinal axis and the runway centerline at touchdown. In order to insure a safe landing the ground track of the aircraft and the longitudinal axis of the aircraft should be coincident along the direction of the runway centerline at touchdown. The decrab problem is illustrated in Figure 40.

Two general techniques for crab angle removal are described in reference 9 as follows:

> "One method of making safe crosswind landings requires a sudden decrab to be performed a few seconds prior to touchdown, so that the wheels become aligned with the runway, yet the inertia of the plane is such that the lateral drift velocity has not had time enough to build up to unsafe values. The wings remain level and the change in heading is produced by rudder action only. This decrab maneuver requires an accurate prediction of the touchdown instant in order that the decrab can be initiated at the proper time. The lateral drive velocity reierred to above is but one of the factors that determine a safe crosswind landing. Other important factors are the heading of the aircraft relative to its ground track and the angular velocity of the plane about its vertical or yawing axis.

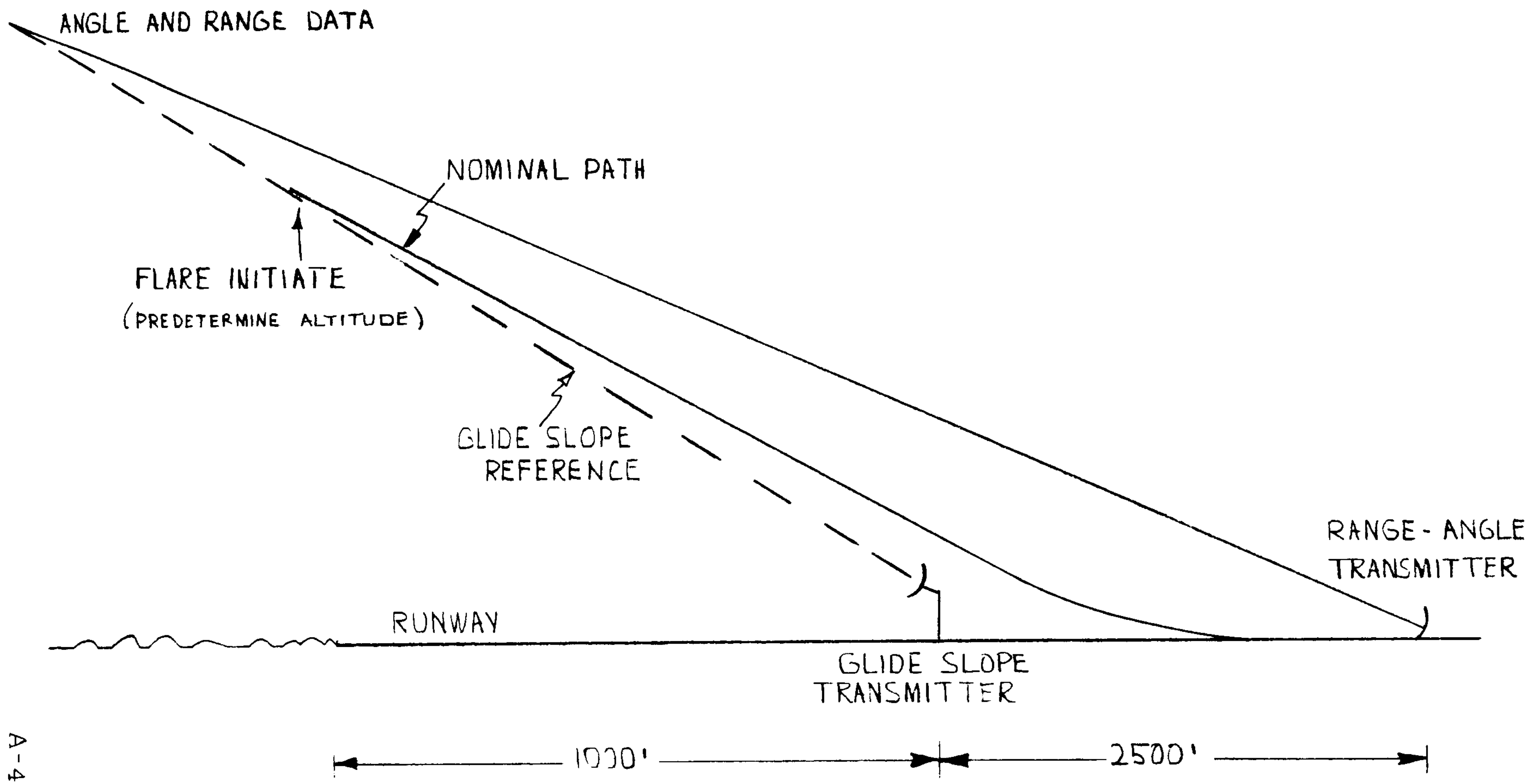


Fig. 39 Range-Angle Exponential Flare Technique

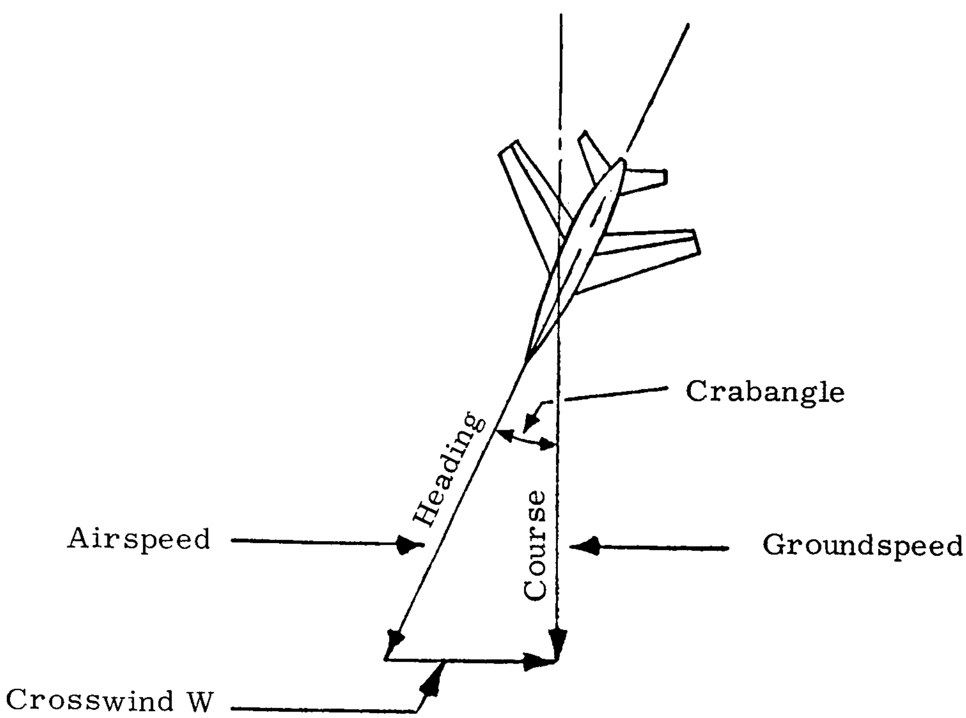


Fig. 40 The Decrab Problem Geometry

These three factors can be combined into one important consideration: the lateral velocity of the landing gear wheels relative to the runway, called v_1 in this report. In a properly executed decrab to the runway heading, v_1 is reduced to a low minimum value in a few seconds after which it rapidly increases. Ideally, touchdown should occur at this minimum so that it is necessary to predict accurately the touchdown instant and to initiate the decrab at the correct prior moment. For large steady crosswinds, even this minimum may exceed safe limits.

"In a more practical system, the rudder is initially hardover and the decrab starts as before. When the maneuver is nearly complete, the rudder moves away from its stops and is allowed to function in a yaw error closing loop to maintain the heading of the plane parallel to the runway centerline. Then, if the touchdown time prediction is somewhat in error, the plane can still land without damaging its landing gear . . ."

The most frequent application of this technique today is to initiate the decrab maneuver at a pre-selected altitude, usually determined by a radio altimeter, and then switch the rudder control to the magnetic compass heading set in by the pilot.

The second technique is characterized as overcompensated crab angle removal:

"A modified form of decrab can be used to extend the crosswind capability by decrabbing through a somewhat larger heading angle so that the plane actually points across the runway toward the down wind side. The percentage increase in the heading command change is not critical in value and provides an easy and effective way of improving the decrab performance. As the plane is pointed toward one side of the runway, appropriate roll-out guidance must be quickly applied to minimize deviations from the runway centerline."

A.6.1 Altitude Initiated, Rudder Controlled Crab Removal Technique

This technique was discussed in a report which presents the results of automatic flareout landing control tests conducted by the Directorate of Flight and All-Weather Testing (11). The following description is provided:

"The test vehicle was a T-33A aircraft with an F-5 (MA-1) automatic pilot. The yaw axis of the automatic pilot was modified to permit a runway magnetic heading command to replace the normal heading command at a pre-selected terrain clearance altitude.

"In order to ascertain crab angle, the gyro-stabilized magnetic heading obtained from the F-5 automatic pilot was used for the actual aircraft heading and summed with the commanded (runway) magnetic heading. Minor modification to the automatic pilot made it possible to switch (automatically at a pre-determined radio altitude) yaw control from the normal configuration to the decrab configuration.

"Variation of the actual height of decrab initiation from the optimum height would result in an increased strain upon the aircraft landing gear. Minimum side loads imposed upon the landing gear under crosswind conditions requires a minimum decrab to be achieved with a minimum cross-runway velocity. This means simply, if the decrab maneuver is executed prematurely the aircraft lateral velocity will be higher than optimum; if decrab is executed too late, less than optimum crab will be removed. Either of these conditions results in the force upon the landing gear being greater than minimum.

"Altitudes measured by a radio altimeter and the altitude for initiating decrab can be pre-selected (before takeoff). Decrab control is not fully automatic. The magnetic heading of the runway to be used must be manually selected on the heading selector at some time previous to landing.

"The decrab technique under test provided no open-loop compensation signal to the roll axis. The normal automatic pilot stabilization of the roll axis was relied upon to maintain the desired wings-level condition during the decrab interval."

A block diagram of this control technique is presented in Figure 41.

A.6.2 Time-To-Go Decrab Initiation Technique

If system input data and computation equipment permits, the decrab maneuver can be discretely initiated as a function of time-to-go. During decrab, it is essential that the wings remain approximately level so that the proper touchdown roll attitude is maintained. The decrab is, therefore, accomplished by a rudder displacement to yaw the airplane through the crab angle, with aileron displacement coordinated to maintain the induced roll angle within acceptable small limits.

Immediately prior to the start of the decrab maneuver, the airplane has a crab angle but is flying very nearly on and parallel to an extension of the runway centerline.

The rudder and bank commands necessary for decrab purposes must be pre-determined. The maneuver is initiated as close to touchdown as possible to avoid lateral offsets which will result from the generation of a sideslip angle. Generally a time-to-go of from 2.0 to 4.0 seconds is used for most aircraft.

A.6.3 Decrab Only Above Maximum Drift Angle

This method will be such that no decrabbing will take place unless the crab angle is greater than a certain angle, say four degrees, which is the normal aircraft limitation for landing. The runway heading signal will be compared with the actual heading, and if the difference is more than four degrees, a signal of pre-determined magnitude (to command a maximum yaw rate) will be introduced into the rudder axis of the autopilot. This will be done at some pre-defined altitude by the radio altimeter, and will be limited to command a safe yaw rate.

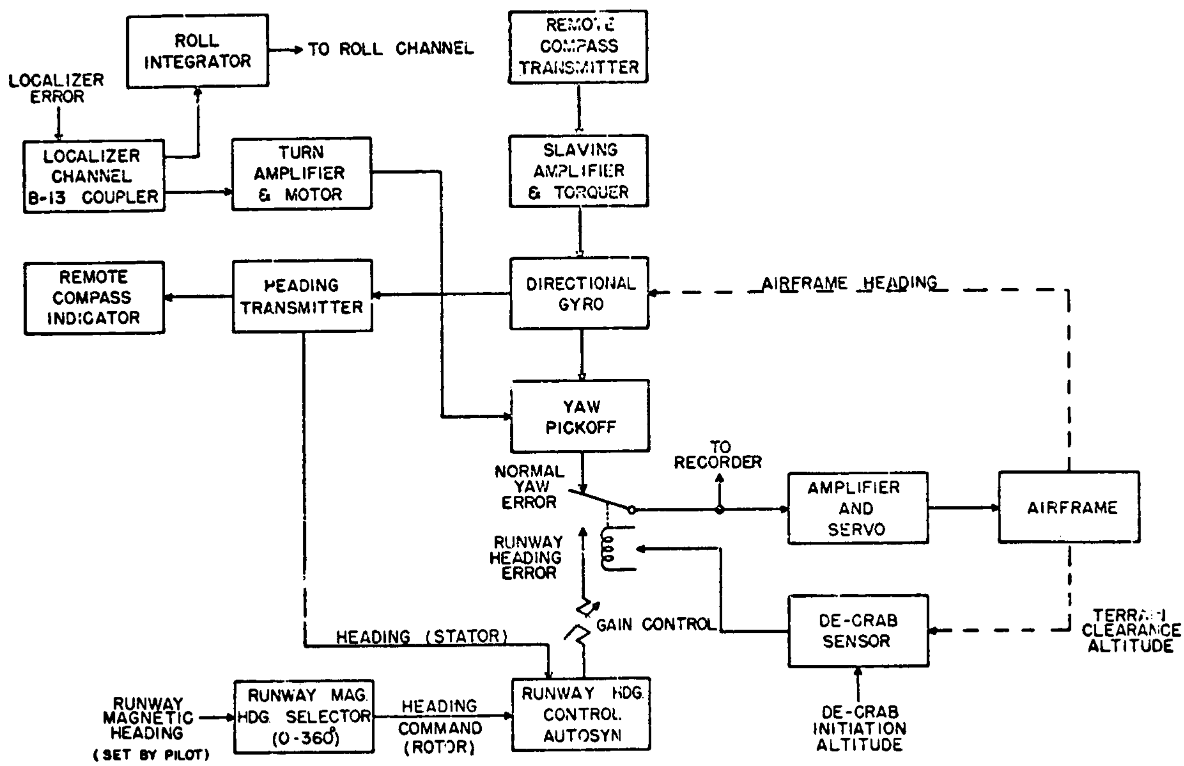


Fig. 41 BLOCK DIAGRAM OF AUTOMATIC RUNWAY HEADING CONTROL

(Taken from Reference 9)

The decrab maneuver will be removed as soon as the airplane reaches the four-degree limit, for two reasons. First, it will prevent excessive decrabbing into the opposite direction which could cause the airplane to drift off the runway rapidly. Second, the airplane will always crab into the wind, and even when decrabbed will not drift off the runway nearly as fast as if the crab angle were returned to zero. This means that the precision of decrabbing time in relation to touchdown time is far less strict.

A.6.4 Side Slip Technique

As an alternative to the decrab technique for either automatic or manual decrab, a coupler utilizing a side slip technique for lateral control is under consideration. This side slip coupler is quite similar to the coupler now being used and would eliminate decrabbing entirely. This technique has the additional desirable feature of maintaining the aircraft line of sight coincident with the runway, thus minimizing the pilot transition problem.

To implement this type of control it is necessary only to insert the runway heading signal into the rudder axis. The beam and beam rate signal are sent to the roll axis in the same manner as in the present coupler. Then if a lateral error is obtained the airplane will bank normally but will be prevented from turning by the very high gain of the runway heading signals into the rudders.

This will produce a slight side slip which will cause the aircraft to move laterally to reduce the beam error rather than by coordinated turning. This condition will result in a coupler control which responds faster in correcting small beam errors. To track the beam it is not necessary to bank the airplane into a turn and when the error is reduced to zero to bank into a turn in the other direction and then to wings level in order to maintain the drag.

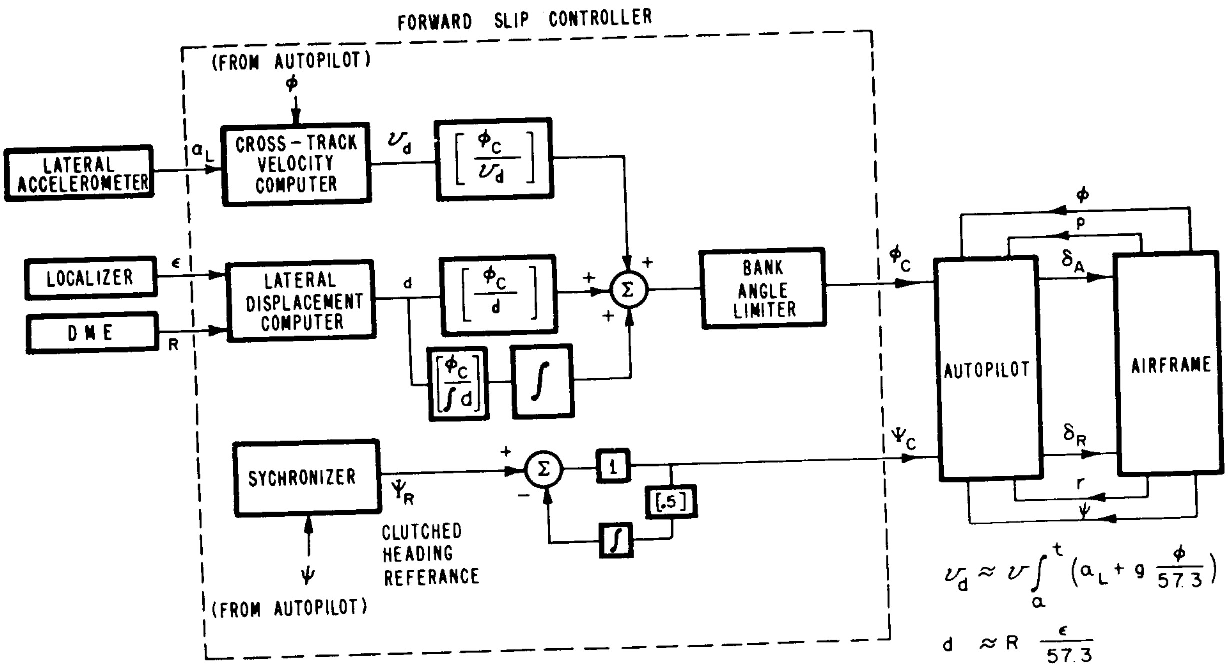
A.6.5 Forward Slip Technique

This technique is described in reference 9 as follows:

"Another type of crosswind landing requires the plane to be pointed along the runway centerline at all times while simultaneously a steady side slip corrects for drift due to crosswind. This maneuver, termed "forward slip", is performed with the upwind wing lowered. Thus, a component of gravity will pull the plane laterally into the wind while the wheels remain aligned with the runway. This banked attitude condition must be maintained by use of the rudder and ailerons, and, when properly executed, results in a side slip at right angles to the ground track with just the right lateral velocity to counter the effect of the crosswind. The wings are less effective in producing lift in this condition and there is an increase in stalling speed. To maintain the proper sinking speed and have an adequate stall safety margin, the indicated airspeed must be increased slightly. The roll attitude will cause the upwind wheel to touchdown first and the turning moment thus generated will set the plane aright quickly and automatically. For many common commercial and military aircraft (especially jet planes) the required roll attitude at touchdown is small (less than 5 degrees). Thus, there is adequate ground clearance of the outboard engine on large multi-jet craft and the rocking over on to both wheels at touchdown is a gentle motion not objectionable to the passengers."

Figure 42 is a block diagram of the forward slip controller, the method of operation is as follows:

"During the approach phase and immediately prior to the initiation of the forward slip, the heading synchronizer follows the plane's heading variations relative to the runway heading, and thus records the crab angle needed to compensate for wind drift. At the start of the maneuver the synchronizer is declutched, and from then til touchdown, it remembers the crab angle at this initial instant. This remembered crab angle is applied to a washout network whose output



$$\mathcal{V}_d \approx \mathcal{V} \int_{a}^{t} \left(a_L + g \frac{\phi}{57.3} \right) dt$$

$$d \approx R \frac{\epsilon}{57.3}$$

Fig. 42 Forward Slip Control System - Block Diagram decreases from this crab angle to zero exponentially with a time constant of approximately 2 seconds. Thus the plane is commanded to decrab exponentially in a controlled fashion (the rudder is not driven hard over) prior to initiating the flare . . .

"Initially there is no cross-track lateral velocity, lateral displacement; thus, the roll autopilot is commanded to maintain zero roll attitude. As the decrab proceeds, the lateral track errors begin to build up because the wind drift is no longer fully compensated. The autopilot is commanded to roll the plane to follow a progressively increasing roll command in an attempt to decrease these errors. The exponential nature of the decrab allows the roll attitude and the resulting side slip component of the lateral drift velocity to catch up shortly and surpass the component due to the remaining uncompensated part of the wind velocity. Eventually the wind drift is once again fully compensated, but now by a side slip into the wind of just the right amount so that the plane is pointed straight down the runway. Touchdown can occur at any time, once the maneuver has been completed, without additional decrab."

A combined decrab and forward slip technique is also described:

"A combined decrab and forward slip maneuver is possible in which part of the lateral drift velocity is corrected by a forward slip and the remainder by a crab angle. Then, just prior to touchdown, a decrab is initiated and the wings are maintained at the forward slip bank angle until touchdown. This combined maneuver requires less of a banked attitude than a pure forward slip and a smaller crab angle than a pure decrab. Unfortunately, however, the amount of rudder deflection available for decrab is now reduced by the amount needed to maintain the forward slip. It appears that a satisfactory landing by either technique alone for the same crosswind condition requires roughly the same amount of available rudder deflection; that the maximum crosswind capability of the airplane is determined by the total available rudder and not by the nature of the maneuver."

A.7 TOUCHDOWN

There are no specific techniques for touchdown per se as the aircraft speed, attitude, and point of contact with the runway are dependent upon the technique used for flareout and decrab. Touchdown may be used to initiate some activities automatically, such as extending speed brakes, retarding the throttle to idle, and disconnecting any automatic control features.

A.8 ROLL-OUT

The basic requirement for the roll-out function is to maintain directional guidance and decelerate the aircraft down the runway until it comes to a complete stop or to a taxiway turn-off which can be safely executed.

It appears that for the near future the primary method for roll-out guidance will be by reference to properly installed visual aid systems rather than by autopilot control. Other techniques are under investigation for solving these problems, but they are somewhat beyond the scope of this report. These techniques under consideration include:

1. Aircraft directional gyro systems
2. Improved ILS localizer techniques
3. IR detection techniques
4. Magnetic field guidance techniques (this can be accomplished with leader cables)
5. Aircraft radar techniques

A.9 GO-AROUND

Go-around is not expected to be an extensive problem with automatic landing systems, since the primary reason for go-around in current landing operations is that the aircraft reaches some altitude and the pilot is unable to make visual contact with the runway. During all-weather operations with automatic landing systems, visual contact is not expected to occur until it is too late for a go-around. Thus the only reason for go-around with the completely automatic system would be malfunction of the system during the approach. The techniques for go-around which are presented below are primarily appropriate to minimum "see to land", rather than "zero-zero", landing conditions.

A.9.1 Precision Radar Go-Around Control

The go-around command can be either manually initiated by a console operator or automatically initiated by the system. Automatic initiation of the waveoff command occurs when any of the following three conditions occur:

(a) the range between two approaching aircraft decreases to a point such that the safety of either or both is impaired; the waveoff command is sent to the aircraft having the greater range,

(b) the aircraft exceeds the limits of an allowable altitude envelope which decreases in size with decreasing range,

(c) the aircraft exceeds the limits of an allowable lateral displacement envelope situated about the runway centerline.

If an automatic go-around is initiated, level flight commands will be imposed on the autopilot since the attitude gyros will return to their reference values. As the aircraft attitude changes in response to these commands, the attitude change will initiate a thrust command. If the aircraft is below the desired glide slope, an increase in thrust is required to return to level flight. The automatic throttle will act to increase thrust without requiring manual inputs. This is particularly important when the aircraft is making its approach below the minimum drag speed since the thrust change must then occur with minimum elapsed time to prevent excessive loss of airspeed.

The manual waveoff command is initiated at the discretion of the console operator.

A. 9. 2 A Technique for Go-Around Control Utilizing Airspeed and Rate of Climb Commands

This go-around system is under consideration for use in conjunction with Category II ILS and, presumably, would be used during the automatic mode of operation.

Redundant go-around signals will be introduced into the existing automatic coupler, so that there will be no switch-over to a basic autopilot which might not be operative at that time. The go-around signals will be introduced into the flare computer through independent switching sources. The two signals will be rate-of-climb command and airspeed command. Either of the signals alone will be able to command a safe go-around. The rate-of-climb command will act as a bias on an instantaneous vertical velocity sensor, and will cause the aircraft to climb at a pre-determined rate considered safe for single-engine operation. The airspeed command will be the actual airspeed signal present in the throttle control system at the moment. This signal will be switched out of the throttle loop and fed to the elevator control loop of the automatic flare system.

In the case of the lateral axis, it is proposed that the localizer beam signals be deactivated; this will cause the airplane to maintain a wings-level attitude.

The go-around will be initiated at any time the airplane is in the final approach mode when the pilot manually overrides the throttle control system by pushing the throttles to their maximum continuous operation position. Analog computer tests indicate that only a 20 foot loss of altitude will occur if the pilot promptly retracts the flaps, speed brakes, and landing gear. The go-around system will be disengaged, and normal autopilot control will be obtained at whatever altitude the pilot actuates the pitch command on the autopilot controller, or selects any other autopilot mode.

A. 9. 3 Speed Command of Attitude and Thrust Technique

The concept of this technique has been excerpted from reference 13:

"This technique is an integrated instrument system that provides both pitch and thrust guidance. By means of both pitch and thrust command, the system maintains the proper speeds and control for dynamic as well as static conditions during takeoff, approach, and go-around.

"There are two basic parameters that are combined . . .: angle of attack and forward acceleration. Each of these parameters provides anticipatory information for the other. Angle of attack change caused by pitch will anticipate change of acceleration. Acceleration change caused by thrust will anticipate change of angle of attack.

"The angle of attack, or lift, is sensed by a small vane located near the leading edge of the wing. The thrust is sensed by a pendulum which is oriented to the pitch gimbal of a vertical gyro. Flap, oleo, and power guadrant switches provide automatic mode selection. The combined signal is presented on the flight director.

"The go-around is accomplished by applying power while rotating to the attitude command. The pendulum responds instantly to the thrust and commands a pitch angle which is exactly related to the change in thrust weight ratio. Repeated go-arounds made Boeing 707 show a maximum altitude loss of less than ten feet from the altitude at which power was applied."

The operating procedure calls for a disengagement of the flight director or autopilot at the point at which the approach is to be abandoned. The system then automatically displays pullout pitch commands on the flight director display for proper guidance during the missed approach. In the approach mode the system is calibrated for 1.3 V_s with 50^o flaps; for 40^o flaps the speed is reference + 10 knots, for 30^o flaps the speed is reference + 20 knots, for 20^o flaps the speed is reference + 30 knots, and for a clean configuration speed is reference + 50 knots. In addition to its display on the flight director command bar where speed is controlled by attitude (takeoff or go-around), information is displayed at all times on a slow-fast meter directly above the airspeed indicator.

APPENDIX B

PILOT QUESTIONNAIRE

* serendipity associates
14827 VENTURA BLVD., SHERMAN OAKS, CALIFORNIA / STate 8-2700

August 6, 1963

Dear Pilot:

Our company is working with NASA's Ames Research Center (Contract No. NAS 2-1346) to study human factors problems in the development of all-weather landing systems. More specifically, we are attempting to study the all-weather landing system problem as a total man-machine system, in which pilot acceptance is one of the requirements the system must meet.

Our concern is not, however, with any specific or early all-weather landing system. We intend to look at each function that must be performed by an all-weather (i.e., minimum visibility) system, and to determine the best method - man, machine, or man-machine combination - for performing each function. Low pilot acceptance will be considered a legitimate argument against automating a function. Our general orientation is that men and machines must be complementary rather than competitive.

To accomplish our research objectives we need to obtain pilot opinion on all-weather landing system functions. We have discussed the problem with pilots here in Los Angeles (and I am an ex-pilot myself) but we need a cross-section of pilot opinion and recommendations from all parts of the country and all airlines. Consequently, we have asked ALPA to send the enclosed questionnaire to a random sample of fifty (50) pilots.

In addition to this random sample (cross-section), we are interested in the reactions of a number of pilots, like yourself, who are known to be more knowledgeable in this area and who are familiar with a wider range of pilot opinion and attitudes. At our request, ALPA provided us with a list of area and regional safety chairmen who they felt would be willing to complete the enclosed questionnaire and perhaps be available for interviews at a later date.

Please complete the enclosed questionnaire at your earliest convenience and return it to us using the addressed envelope. To help us in planning our interview schedule please complete the attached form to indicate if you would be willing and available for a follow-up interview. Interviews are necessary as the complexity of the ALS problem makes it impossible to obtain sufficient information by questionnaire.

Thank you for your cooperation on this project.

Sincerely,

Ewart E. Smith
Senior Scientist

*An Incorporated Professional Group: Ewart E. Smith / Harold E. Price / Kay Inaba

NAME ________________

DATE ________________

PILOT QUESTIONNAIRE

ALL-WEATHER LANDING SYSTEMS

1. Airline ____

2. Your usual equipment ________________________________

3. Your usual route(s) ________________________________

____
(Specify major terminals, e.g., LAX, DCA, etc)

4. Usual Flight Position: Captain ________ 1st Officer ________

5. Additional Ground Positions: ________________________
(e.g., Safety Chairman)

6. Approximate Total Airline Flying Hours: Jet ________ Prop ________

7. Age ________ 8. Years Pilot Experience ________

9. Approximate total military flying hours ________________

10. Principal military aircraft type: Transport ________________

Bomber ________________

Fighter ________________

11. Please indicate the extent to which you are familiar with all-weather landing system concepts and proposed automatic flight control techniques (circle one):

A. Informal reading and discussion with other pilots.

B. Have had some contact with the technical literature and/or well-informed individuals.

C. Have thoroughly studied technical literature and/or attended formal technical presentations.

D. Have had direct contact with development projects for at least one automatic control technique.

E. Have participated in actual approach and landing under automatic control.

12. What are the lowest minimums you are currently cleared for? (any airport):

Ceiling ________________

RVR ________________

13. If your current aircraft is equipped for ILS - autopilot coupled approaches, or if you have ever flown an instrument approach using the coupler, please indicate your opinion of this technique below. Check one statement, which best expresses your evaluation of the coupler for an instrument approach.

________ (1) The technique is superior to manual control and I use it with complete confidence.

________ (2) The technique is a good one and I use it with confidence, but there are features I dislike.

________ (3) This technique is marginally adequate for an instrument low approach and I am not completely confident when required to use it.

________ (4) I would use this technique but without confidence and would therefore require high safety margins.

________ (5) I would not use this technique for an instrument approach.

INSTRUCTIONS FOR NEXT PAGE

14. The principal flight control functions which occur during a generalized approach and landing are listed on the following page. Please consider each function and indicate your acceptance of automatic equipment for performing the function. Use the acceptance code below to assign one letter to each function. Please comment as freely and fully as you like in order to clarify or qualify the coded acceptance statement you adopt. Extra space for comment is provided at the end of this questionnaire. Remember that you are indicating your degree of acceptance of automated control devices for an approach and landing without visual reference, i.e., for "blind" landings.

A. Highly acceptable I would use automatic equipment for this function.

B. Acceptable I will use it but with some reservations.

C. Uncertain I'm not sure yet how I feel about it, will probably be influenced by others and further developments.

D. Unacceptable I will agitate against it, only use it if forced to by its adoption by the industry and ALPA.

E. Completely unacceptable I will not use it, even if it is approved by my company, FAA and ALPA.

14. (Continued)

Flight Control Function	Your acceptance of automation (Check one-using code on preceding page) A	B	C	D	E	Comments
1. Initial acquisition of the approach and landing guidance system (e.g., start receiving guidance signals).						
2. Horizontal flight path control (e.g., intercept and hold ILS localizer and/or alignment with runway).						
3. Establish and maintain proper airspeeds throughout landing sequence.						
4. Vertical flight path control (e.g., maintain initial approach altitude, acquire and hold glide path).						
5. Final evaluation of approach and decision to land.						
6. Execute flareout.						
7. Remove drift correction just prior to touchdown.						
8. Touchdown.						
9. Directional control on roll-out.						
10. Abort approach and execute missed approach procedure.						

15. All-weather landing systems currently under development or being proposed will provide for different degrees of automation, i.e., from completely "hands off" to manual blind landings by instrument reference. Please indicate your opinion of the most acceptable degree of automation by ranking the following alternatives. Place the number 1 beside the alternative you feel is most acceptable and the number 5 beside the least acceptable alternation with the others ordered in between.

______ (1) Completely Automatic - Once turned on and adjusted, operation is completely automatic. Monitoring is also automatic and a duplicate system would take over in event of malfunction. Pilot participation not required and pilot interference (except turn-off) not provided for.

______ (2) Automatic with Pilot Interaction - Basic operation is automatic but active pilot monitoring is required. Provisions made for pilot input of commands, e.g., pilot selects airspeed to be maintained automatically. Pilot takes over in event of malfunction of primary automatic system.

______ (3) Split-Axis Control - Concurrent pilot and automatic control, e.g., system allows pilot to control pitch axis manually while autopilot controls rudder and ailerons.

______ (4) Computer Commanded Manual Control - Pilot controls aircraft manually by reference to computed pitch, roll, or other steering commands.

______ (5) Manual Control-Situation Display - Pilot controls aircraft by reference to flight situation display only, i.e., deviation from desired flight path, attitude, rate of descent, altitude, etc., is provided but no command display calling for pilot to assume specific attitude or airspeeds is provided. Pilot continuously determines necessary corrective actions.

16. Please indicate how you feel about the following:

	Agree Very Much	Agree	Don't Know	Disagree	Disagree Very Much
	Check one				
a. A pilot requires information on how an automatic system is correcting error as well as information on what error exists.					
b. Pilots of large jet aircraft cannot respond quickly enough to take over and land manually if an autopilot failure occurs at 100' altitude.					
c. "Blind" or "zero-zero" landings can only be accomplished using "hands off" automatic control as situation or flight director displays cannot provide adequate information for human judgment and control in critical phases of the landing.					
d. Pilots do not like to use automatic equipment (such as the ILS coupler) because they enjoy doing complex flight tasks themselves.					
e. Automatic landings will be common and accepted within the next decade or so.					
f. More extensive use of automatic equipment will eventually make the public think being a pilot is a less important job.					
g. Except for equipment malfunction, go-arounds should not be required using automatic control, even when visual contact with the runway or visual aids cannot be established.					

16. (Continued)

	Check one				
	Agree Very Much	Agree	Don't Know	Disagree	Disagree Very Much
h. Instrumentation (displays) should be provided which will allow the pilot to land the airplane manually without external visual reference.					
i. The displays cited in Item h. need contain no computed flight director or command information.					
j. Automatic equipment will eventually mean fewer jobs for pilots.					
k. Pilots must be kept in the control loop, not only as equipment mode selectors and monitors, but so that they can enter the loop at any time to override automatic control or to abort the approach.					
l. Automatic touchdown is more acceptable than aborting an approach when a visual landing cannot be assured at 100 feet.					
m. All-Weather landing operations cannot mean "blind landings" as some form of visual aid, such as runway center-line lighting, will be required to monitor an automatic landing.					
n. Suitable means should be provided to prevent the pilot from interferring with automatic devices, once the minimum safety level compatible with the information available to the pilot has been reached.					

17. Do you have any additional comments or suggestions?

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